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A METHOD FOR ESTIMATING THE COST OF AIRCRAFT STRUCTURAL MODIFIC--ETC(U)
MAR 81 J L BIRKLER, J P LARGE F49620-77-C-0023
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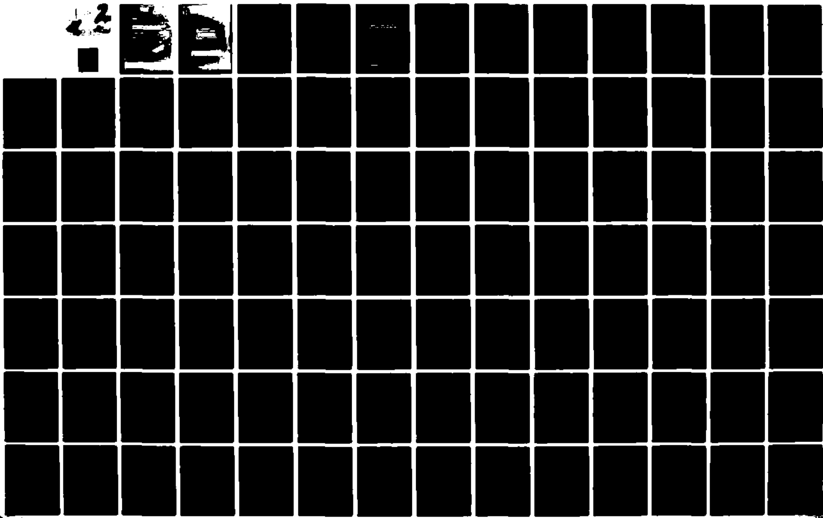

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Describes research into the cost of aircraft structural modifications. Detailed cost and man hour data supplied by the airframe industry permitted derivation of estimating tools for major aircraft components. Separate equations were derived for engineering, tooling, manufacturing, and material cost. The major explanatory variable was always weight. It was hypothesized that structural modification cost could be estimated on the basis of the weight of material added. Estimates of the cost of modification for the B-52, C-141, C-5, and EF-111 were compared with cost data from industry. Considerable informed judgment is required as is a knowledge of such program-specific facts as whether the original production tooling still exists. Rather than a mathematical model, the study describes the kinds of information needed, suggests guidelines, and presents estimating equations for airframe systems and subassemblies. These contribute to an understanding of the estimating problem but do not constitute a general solution. 146 pp. (Author)

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A Method for Estimating the Cost of Aircraft Structural Modification

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A Project AIR FORCE report
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PREFACE

This report describes the results of research undertaken in cooperation with the Directorate of Cost Analysis, Aeronautical Systems Division, Air Force Systems Command, into the cost of aircraft structural modification. The objective of the research was to develop generalized estimating methods suitable for planning studies, Independent Cost Analyses (ICAs), and other situations for which conventional detailed engineering estimating procedures are either impracticable or overly time-consuming.

The research did not yield a well-ordered set of parametric and deterministic estimating equations analogous to the Rand model for airframe and turbine engine development and production costs.[1] The report does present, however, a combination of estimating equations, comparative data, and narrative information that provides a generalized method for cost estimation and analysis. The results should be of interest to persons throughout the Air Force and elsewhere in the Department of Defense who are concerned with the preparation or review of airframe structural modification costs.

The research reported here was undertaken as part of the Project AIR FORCE project "Cost Analysis Methods for Air Force Systems."

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[1] H. E. Boren, Jr., A Computer Model for Estimating Development and Procurement Costs of Aircraft (DAPCA-III), R-1854-PR, March 1976.

SUMMARY

As budget constraints and high unit acquisition costs have combined to limit the development and production of new military aircraft, modification of in-service aircraft has become increasingly important. Within the past few years funds budgeted for modification of Air Force aircraft have grown from several hundred million dollars annually to well over a billion. That shift in emphasis has created a need for a procedure to estimate modification costs early in the planning cycle, when resources are limited and detailed knowledge of design specification is unavailable.

Parametric estimating models requiring few inputs have been found to provide cost estimates of aircraft that are sufficiently accurate for preliminary planning and tradeoff studies. The premise of the present study was that it might be possible to develop a comparable model for estimating aircraft modification costs.

The study was conducted in conjunction with the USAF Aeronautical Systems Division's Cost Analysis Directorate and in cooperation with major U.S. aircraft manufacturers. Detailed cost and manhour data supplied by the airframe industry were used to prepare estimating methods for all major aircraft components--wing, empennage, landing gear, etc. Separate techniques were derived for the engineering, tooling, manufacturing, and material cost categories. In every case the major explanatory variable was weight. It was hypothesized that the cost of a structural modification could be estimated on the basis of the

"new" weight involved--the weight of material to be designed, fabricated, assembled, and added to the airplane.

The equations were used to estimate the cost of actual modification programs for the B-52, C-141, C-5, and EF-111. Those estimates were then compared with cost data from industry on those programs. It became clear that a simple deterministic model would not provide reliable estimates of aircraft modification costs. Considerable informed judgment is required, plus a knowledge of program-specific facts, such as whether tooling from the original production program is still in storage.

Consequently, this report presents an estimating procedure rather than a mathematical model. The procedure describes the kinds of information needed, suggests guidelines for estimating, and presents estimating equations for airframe systems and subassemblies. Taken together, these contribute to an understanding of the problem of estimating modifiication costs. They do not constitute a general solution to the problem.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to members of the Aeronautical Systems Division/Industry Cost Estimating workshop, especially its present and former chairmen, C. E. Porter and C. Adams. Many members of this organization provided support and advice that enhanced our understanding of the modification process.

We are also grateful to the following major airframe companies: Boeing Military Airplane Company, Fairchild Republic Company, General Dynamics Corporation, Grumman Aerospace Corporation, Lockheed-Georgia Company, Lockheed-California Company, McDonnell Aircraft Company (St. Louis), McDonnell Douglas Corporation (Long Beach), Northrop Corporation, Rockwell International Corporation, and Vought Corporation. Their willingness to provide data and share insights made possible the analysis described here.

J. D. S. Gibson, Directorate of Cost Analysis, Air Force Systems Command, and H. Ring, Cost Analysis Division, Air Force Logistics Command, thoughtfully reviewed an earlier draft of this report. Several Rand staff members provided advice and assistance in the course of this investigation, notably B. Bradley, H. Campbell, and R. Hess. All provided constructive comments that have led to many improvements. L. Batchelder assisted with data preparation.

CONTENTS

I. INTRODUCTION

The U.S. Air Force modifies aircraft and the associated ground support and training equipment for three major reasons: to improve safety, to extend the service life of the equipment, and to incorporate operational improvements. The FY80 modifications program, for example, included the following objectives:

- Increasing the strategic airlift capability.
- Updating the penetration and electronic defense capabilities of various weapon systems.
- Improving aircraft navigation capability to permit continued operation within the increasingly congested airspace.
- Updating the capability to detect and counter or destroy hostile offensive ground systems.
- Providing a tactical-support jamming capability.
- Increasing the reliability of operational systems by replacing obsolete vacuum-tube equipment with solid-state equipment.

The Air Force procurement budget shows that over $600 million has been allocated annually for such modifications in recent years and beginning in FY 1979 those allocations began a sharp upward trend. The total obligational authority for FY 1980 was nearly $1.6 billion. These figures do not include the cost of incoming processing and final delivery for the aircraft or of installing modification kits. In the case of most major modifications such installation costs are high.

The bulk of the funding for modifications typically goes for avionics--communications, navigation, electronic countermeasures, and penetration aids. Major structural modifications are undertaken less frequently, although programs such as the C-141 fuselage stretch and the proposed rewinging of the C-5A are significant in both scale and cost. The C-5A rewinging, for example, is expected to cost over a billion dollars. In spite of such large amounts, modification of in-service aircraft is often substantially less costly than the development and procurement of new aircraft.

Modification costs are ordinarily estimated in great detail, frequently by the application of standard engineering and manufacturing hours to each operation in the modification process and building up to a total. Whatever the degree of accuracy obtained through this process, it is very time-consuming and requires a detailed knowledge of the proposed modification as well as up-to-date information on standard hours for the various fabrication and assembly procedures. For planning studies, preliminary tradeoff analyses, Independent Cost Analyses (ICAs) and the like, it would be desirable to have a simple procedure for estimating the cost of such major structural modifications. Consequently, with the assistance of the Directorate of Cost Analysis at the Aeronautical Systems Division and major airframe contractors, Rand agreed to attempt to develop an alternative procedure that could be used to obtain estimates quickly and with a modest amount of descriptive information (e.g., airframe characteristics). Such a procedure would be used only prior to or early in the planning and development phase of a major modification program, when no drawings exist and the contractor

may not have been selected. By the time development is well along and an estimate of production cost is needed, greater accuracy can be achieved by projecting from actual costs of prototypes than by the generalized and largely parametric methods described here.

The premise of this study was that using data on production aircraft it might be possible to develop parametric equations for modifications of the type that have proved use-ful for estimating aircraft, airframe, and engine costs. Section II describes how data were collected and analyzed to obtain parametric equations for the various aircraft subassemblies and systems. Section III through VII treat each of the major functional cost elements: engineering, tooling, production, quality control, and manufacturing materials. Estimating equations are presented and applied to major structural modification programs on four aircraft--the B-52, C-141, C-5, and EF-111. The estimates obtained are compared with the cost and manhour data supplied by industry for these programs to obtain a measure of the utility and limitations of the estimating procedure. Section VIII presents the conclusions. Appendix A presents an example of how the procedures discussed in the report could be used to estimate the cost of a hypothetical wing modification program, and Appendix B gives plots of the data collected.

II. RESEARCH PROCEDURE

A survey of estimating procedures showed that a few major airframe companies, most notably McDonnell Aircraft Company, routinely use parametric methods to estimate modification costs. In those cases satisfactory use depends on having collected and stored manhours and costs by functional element (engineering, tooling, etc.) for all aircraft structural assemblies and subsystems--wing, empennage, landing gear, fuel system, etc.--for every aircraft manufactured. With such a data bank in hand, if a change is proposed that involves a specified number of pounds of new weight in a wing, fuselage, or other assembly, a manhour or cost factor may be applied to the weight to obtain a modification estimate.

That method works well for companies that have the detailed information needed, but the information cannot be obtained directly from accounting records; much of it is developed by allocation, and allocation procedures differ among the few companies that organize data in this manner. The Air Force would find it impractical to rely on having a set of estimating factors for each aircraft in the inventory, because such factors were not recorded for many aircraft, and where they do exist, their content is not comparable among companies. For the purpose at hand the parametric approach is the most appropriate, and it is the only approach considered here.

The basis for any parametric estimate is the known relationship between one or more independent variables and a dependent variable. The assumption commonly made in the airframe industry is that cost is

related to weight: when the weight of a new aircraft is known, cost can be estimated reasonably well. That oversimplifies the estimating procedure, because a number of other variables must be considered as well; but for estimating modification costs, weight is the dominant variable. Generally, "new" weight is used. New weight is not the incremental weight resulting from a modification; it is the weight of material to be designed, fabricated, assembled, and added to the airplane. In a KC-135 wing modification of a few years ago, for example, approximately 8600 lb were removed from the aircraft and 9334 lb of new weight were added. The 9334 lb would be used to estimate modification costs, rather than the 734 lb net change.

The new weight in a proposed modification normally includes more than one aircraft section. A wing modification, for example, could include fuselage structure and flight controls, and an estimator would need a different factor for each. In its simplest form, then, the estimating procedure would be to multiply a manhour or dollar factor by the number of pounds of new weight for each aircraft assembly and subsystem. Of course, the estimating procedure is not that simple even when factors or equations are available for each aircraft group, but to develop estimating relationships it was necessary to collect manhour and cost data on a sample of military aircraft large enough to support statistical inferences.

DATA

Among the airframe companies, McDonnell Aircraft Company is the foremost proponent of parametric estimating; that company has accumu-

lated detailed costs on all McDonnell fighter aircraft produced during the past 20 years or more. From their experience we believed it would be possible to obtain actual costs by aircraft section and subsystem--segregated into nonrecurring and recurring categories--for most military aircraft developed and produced in the United States since 1960. Most contractors apparently do not have data of that kind, however, and some have such data only on their most recent aircraft. Table 1 shows the aircraft and aircraft groups for which data were obtained. Much more information is available on structural assemblies than on subsystems, and much more on current aircraft than on older ones. Sample sizes for the various cost elements range from 1 to 13.

The categories in Table 1 do not provide the flexibility an estimator would like to have. First, no two companies record data in the same set of structural and subsystem categories, so to obtain a sample large enough for statistical analysis one has to combine categories, then develop an estimating equation for, say, the total fuselage rather than the forward, mid, and aft sections. Second, contractors not only differ in their choice of categories, they also differ in deciding what to include in the various aircraft groups. Flight control, for example, may or may not include hydraulics. Environmental control could be a separate category or it could be included with Furnishings and Equipment; in one case it was aggregated with another system and called Other Airframe. Thus the definitional problem is perverse and serious.

A third problem is the different allocation schemes adopted by the various companies. By allocation we mean the way in which hours are attributed to each section or subsystem. Typically, airframe contractor

Table 1

AIRCRAFT GROUP DATA BASE

(Summary of data sample available for engineering, tooling, production, and material)

Aircraft Group \ Aircraft	A 6	A 7	A 10	B 52	C 5	C 130	C 141	F 4	F 14	F 15	F 16	S 3	KC 135
Wing	E T P	E T P M	E T P	E T P	E T P M	E T P M	E T P M	E T P M	E T P M	E T P M	E T P M	E T P M	E T P
Fuselage	E T P	E T P M	E T P	E T P	E T P M	E T P M	E T P M	E T P M	E T P M	E T P M	E T P M	E	E T P
Fwd	E T P	E T P M		T P			P M	E T P M	E T P M	E T P M	E T P M		T P
Mid	E T P	E T P M		T P			P M	E T P M	E T P M	E T P M	E T P M		T P
Aft	E T P	E T P M		T P			P M	E T P M	E T P M	E T P M	E T P M	E T P M	T P
Empennage	E T P	T P M	E T P	E T P	E T P M	E T P M	E T P M	E T P M	E T P M	E T P M	E T P M	E T P M	E T P
Landing Gear	E T P	E P M	E	E T P	E T P M	E T P M	E T P M	E T P M	E T P M	E T P M	E T P M	E T P M	E T P
Flight Controls	E	E T		E	E T P M	E T P M	E T P M	E T P M	E T P M	E T P M	E T P M	E	E
Hydraulics	E T P	E		E	E T P M	E T P M	E T P M	E T P M	E T P M	E T P M	E T P M	E	E
Electrical	E	E			T P M	E T P M	E T P M	E T P M	E T P M	E T P M	E T P M	E	E
Propulsion	E T P	E		E T P	E T P M	E T P M	E T P M	E T P M	E T P M	E T P M	E T P M		E T P
Fuel System	E T	E	E	E T P			E T P M	E T P M		E T P M	E T P M		E T P
Avionics	E T	E		E	E T P M	T P M	E T P M			E T P M	E T P M	E	
Environmental Control System	E T	E	E		E T P M	E T P M	E T P M				E T P M		E
Furnishings & Equipment	E	E			E T P M	E T P M	E T P M	E T P M	E T P M	E T P M			
Integration	T P	E	E		E T P M	E T P M	E T P M		E T P M		E T P M	E	
Other Airframe				E P					E T P M				E
Crew Station		E									E T P M		E
Final Assembly		P M		T P				P M		P M	E T P M		T P

E Engineering
T Tooling
P Production
M Material

accounting systems identify certain hours by aircraft section; other hours are not as easily identified as belonging to a given subsystem or section and they must be allocated over all sections in a logical manner. Unfortunately, one contractor's logic does not apply equally to the rest, so inconsistency results. Various methods are used; allocable hours may be spread to each section on the basis of either identified hours or subsystem weight. The amount of hours to be allocated will vary, so that certain companies may allocate a large percentage and others less. Fairchild stands out at one extreme, because they report only the hours and costs that can be attributed directly to an aircraft group. The remaining manhours, 40 percent of the total in one case, are not allocated.

A fourth problem is that a given company will not always report the same labor hours and material costs. In some cases the company will convert subcontract costs into hours and material costs and add them to inhouse labor and materials. In other cases, all subcontract costs are included with material costs. Wherever the latter procedure was detected, out-of-plant work was converted to hours and material and allocated among the aircraft groups; but detecting such discrepancies would require a more detailed examination of records than this study permitted.

A final problem is the need to normalize data received from different companies for quantity. We asked for data so that it would be possible to plot cost-quantity curves and obtain hours and costs for all aircraft in the sample at the same quantity. In some cases, the

data and cost-quantity curves were further adjusted based on discussions with the manufacturers or analysis of the most recent production lots. In other cases, lines were extrapolated along the established slope to obtain a value for a greater number of aircraft than were actually built; for example, only 81 C-5As were produced, but we extrapolated the cost-quantity curve out to the 100th unit to keep sample size constant for all aircraft.

After we made all the adjustments to the data, we calculated the percentage of cost attributed to each aircraft group for the major cost elements for each aircraft in the sample. Those percentages, when compared as in Table 2, showed clearly that differences among contractor practices were so great that statistical analyses of some of the aircraft groups would be meaningless. System integration, for example, is an important engineering function, but half of the aircraft displayed in Table 2 have no manhours allocated to it. For each cost element, the data that constituted each group sample were scrutinized for consistency and reasonableness. When our investigation revealed data not of the same quality as other data points making up the group, the point in question was not included in the subsequent analysis. Most often, however, an unusually low or high value could be explained (for example, one aircraft was supersonic and the others were subsonic); these values remained in the group sample, which was then analyzed. Table 3 shows the number of data points by cost element considered sufficiently homogeneous to support analysis. No unequivocal definitions can be given for the various aircraft groups, but the information below can be used as a guideline.

Table 2

ALLOCATION OF ENGINEERING[a]

(Percent of engineering hours spent on Unit 1)

Item	A-6	A-10	B-52	C-5A	C-130A	C-141A	F-4	F-14A	F-15	F-16	KC-135
Wing	12.5	16.3	12.0	17.3	12.0	19.3	17.0	7.1	9.7	2.6	11.2
Forward fuselage	17.5						16.5	9.2	10.5	4.0	
Mid fuselage	10.7	18.6	13.1	33.9	22.8	20.8	13.7	17.6	10.7	2.5	15.4
Aft fuselage	4.0						5.8	12.1	11.8	2.6	
Empennage	2.7	3.4	--	4.9	9.0	5.1	2.4	2.3	4.1	1.7	2.8
Landing gear	3.5	3.7	0.4	5.0	4.0	1.8	3.6	4.3	4.0	1.7	0.7
Fuel system	2.5	--	8.2	--	--	--	4.9	--	4.9	2.2	20.2
Propulsion	3.4	--	1.4	7.3	11.4	1.7	--	7.8	--	--	11.6
Flight controls	11.2	38.5	6.4	3.3	9.9	5.6	12.0	8.8	11.5	6.1	3.2
Hydraulics	1.7	--	3.0	2.1		4.3				2.6	2.6
Electrical	0.4	--	--	--	8.7	6.7	8.8	6.2	5.3	15.5	4.2
Environmental control systems	3.1	0.7	--	2.0	8.0	3.5	--	--	--	2.9	2.2
Furnishings	1.0	--	--	2.0	4.6	4.2	10.6	6.2	6.3	--	--
Avionics	--	--	15.3	5.4	--	4.9	--	--	18.1	30.1	--
Integration	--	12.2	--	14.1	--	9.7	--	1.3	--	18.4	--
Engine installation	--	--	--	--	--	--	4.9	--	3.2	2.1	--
Electronics	16.6	--	--	--	--	--	--	--	--	--	--
Nacelles	--	6.6	--	--	--	--	--	--	--	--	--

[a]Percentages do not necessarily total to 100 percent.

-- Not available.

<u>Wing</u>: For large aircraft (B-52, C-141, C-5 and A-10) the center section is included. For smaller aircraft (A-6, F-4, F-14, F-15) it is excluded.

<u>Forward fuselage</u>: Includes canopy and windshield.

<u>Mid fuselage</u>: Includes center wing except as noted above and air induction system where applicable.

<u>Aft fuselage</u>: Includes speed brakes.

<u>Empennage</u>: Includes stabilizer, fins, elevator and rudder.

<u>Landing gear</u>: Excludes wheels and tires.

<u>Electrical</u>: May include instruments and Auxiliary Power Unit.

Table 3

NUMBER OF DATA POINTS AVAILABLE FOR ANALYSIS

Aircraft Group	Engi-neering	Tooling	Manufac-turing	Material
Wing	9	10	13	7
Fuselage	12	10	13	8
Forward fuselage	6	7	9	6
Mid fuselage	4	8	7	6
Aft fuselage	7	9	8	6
Empennage	8	9	12	7
Landing gear	12	11	12	8
Electrical	9	6	7	7
Controls and hydraulics	12	7	7	6
Furnishings and equipment	8	7	7	7
Environmental control	8	6	5	5
Propulsion total	9	10	10	6
Fuel system	6	6	6	4
Propulsion system	5	5	7	4
Avionics	7	6	5	4
System integration	5	7	8	5

Controls and hydraulics: Flight controls (but not flight surfaces), hydraulics, and pneumatics.

Furnishings and equipment: Includes crew station equipment, furnishings, emergency equipment.

Environmental control: Includes air-conditioning and anti-icing.

Propulsion-total: Includes afterburner support structure, thrust reverser, and tanks.

Fuel system: Excludes tanks.

Propulsion system: Includes engine controls and lubricating system.

Avionics: Covers installation of, but excludes cost of, purchased and government furnished equipment.

System integration: Includes joining and installation operations for airframe structure and nonstructure, as well as installation and testing of systems.

ANALYTICAL PROCEDURE

After all the manhours and dollars were normalized as described above, curves were fitted by regression analysis to these data points to obtain a unit 1 value and a cost-quantity-curve slope. The unit 1 value represents all nonrecurring plus recurring hours for engineering and tooling. No nonrecurring costs are included in the other cost elements--production and materials. With the curves obtained, values were then calculated for cumulative average costs at unit 100. Next, regression analysis was used to develop and estimating equation by cost element for each group at the 100th unit.

Two criteria were established before a variable was tested for significance:

1. The variable had to be logically related to manhour or cost.
2. The variable had to be known with a fair degree of accuracy during the concept formulation phase.

The search for suitable explanatory variables began with group weight. Group weight is a logical candidate because it is an indicator of size, and, all other things equal, a large aircraft structural subassembly should cost more than a small one.[1] Design considerations indicated, as have previous Rand studies, that speed--maximum speed in knots--should also be an important independent variable. Despite the intuitive appeal of such reasoning, speed appears as an explanatory variable in only one equation (see Fig. 1). For some aircraft groups, our analysis indicated a difference between supersonic aircraft and subsonic aircraft (supersonic aircraft seem to require more expensive materials, as well as more hours to design and produce); however, because of the smallness of the sample sizes, the predictive quality of such equations was questionable. Other variables or combinations were found not to be statistically significant, and we concluded that group weight and aircraft speed were the most dependable predictors of cost.

Of course, aircraft characteristics alone cannot explain variability in program costs. Schedule, management, funding, state-of-the-art advance, availability of labor, investment in capital tools all affect cost but cannot be captured in a simple model. A parametric cost model based on data from a wide assortment of programs is not sensitive to

[1] Certain airframe contractors consider group weight privileged information. Therefore, these data cannot be included in this report.

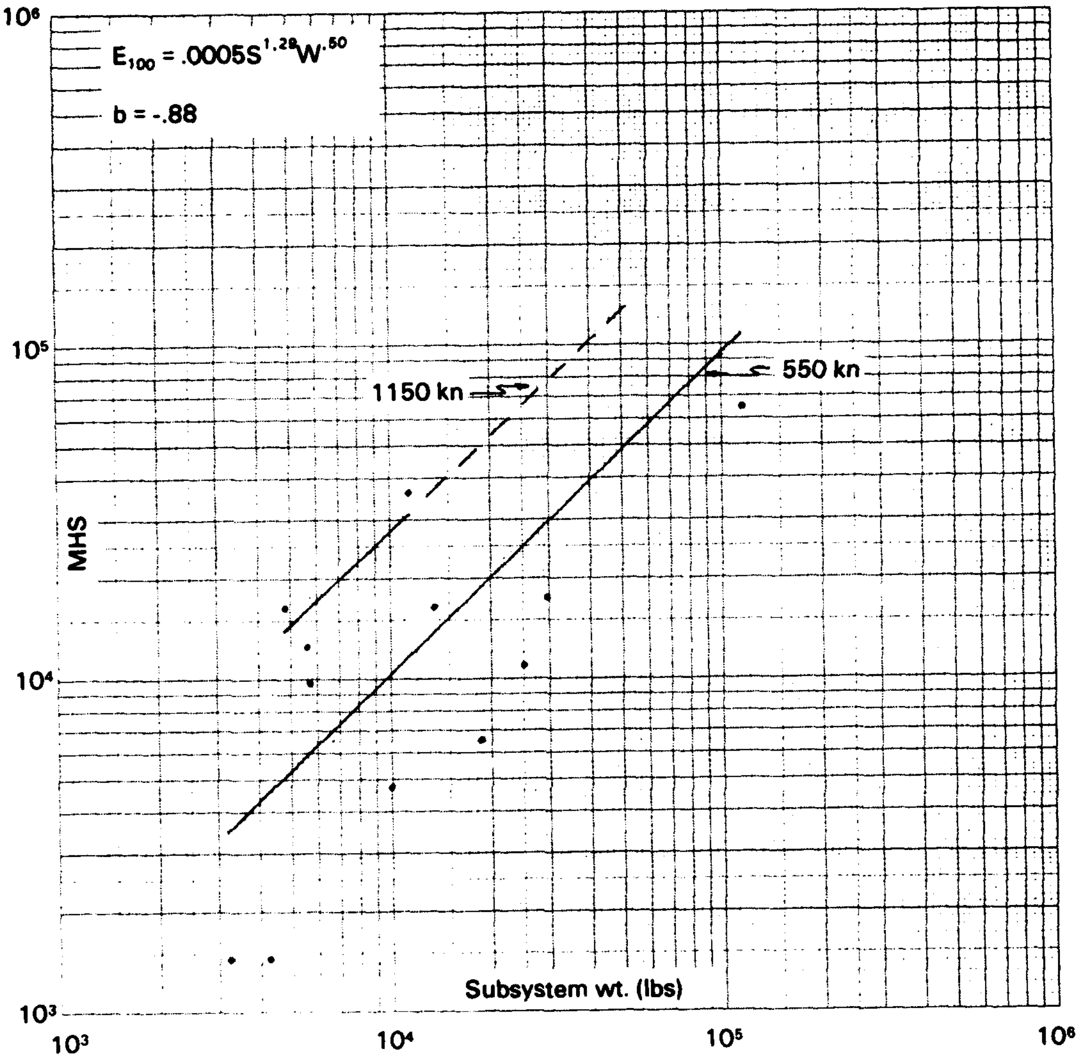

Fig. 1—Engineering MHS* vs fuselage weight

*100th unit cum ave value

small changes, and it assumes that every program will have its fair share of technical, programming, and funding problems. Only when an explanatory variable demonstrates a consistent and perceptible influence on a variety of programs can it be included in a cost model.

The multiple-regression computer program used calculates the usual statistical measures of fit--coefficient of determination, standard error of estimate, and F-value. In general, when selecting preferred equations throughout this study we looked for a high coefficient of determination (R^2), a low mean absolute percentage of Y-deviations, and a level of significance for all independent variables of at least 90 percent.

No defensible statistical equations could be obtained for a number of the aircraft groups. Lack of a statistically acceptable estimating equation does not obviate the need to make estimates, however, so available data were plotted on log-log scales (see App. B.). When a trend was discernible, a line was visually fitted to the data and an equation derived based on the line. Figure 2 provides an example of this method. If no trend was evident, the plotted data were shown in a shaded region (see Fig. 3). (Even though no equation can be derived, such data can often prove valuable when no other information exists.)

Table 4 shows a summary of estimating methods resulting from the above analysis. The equations and graphs that follow represent the cumulative average hours or costs through the 100th unit. A cost-

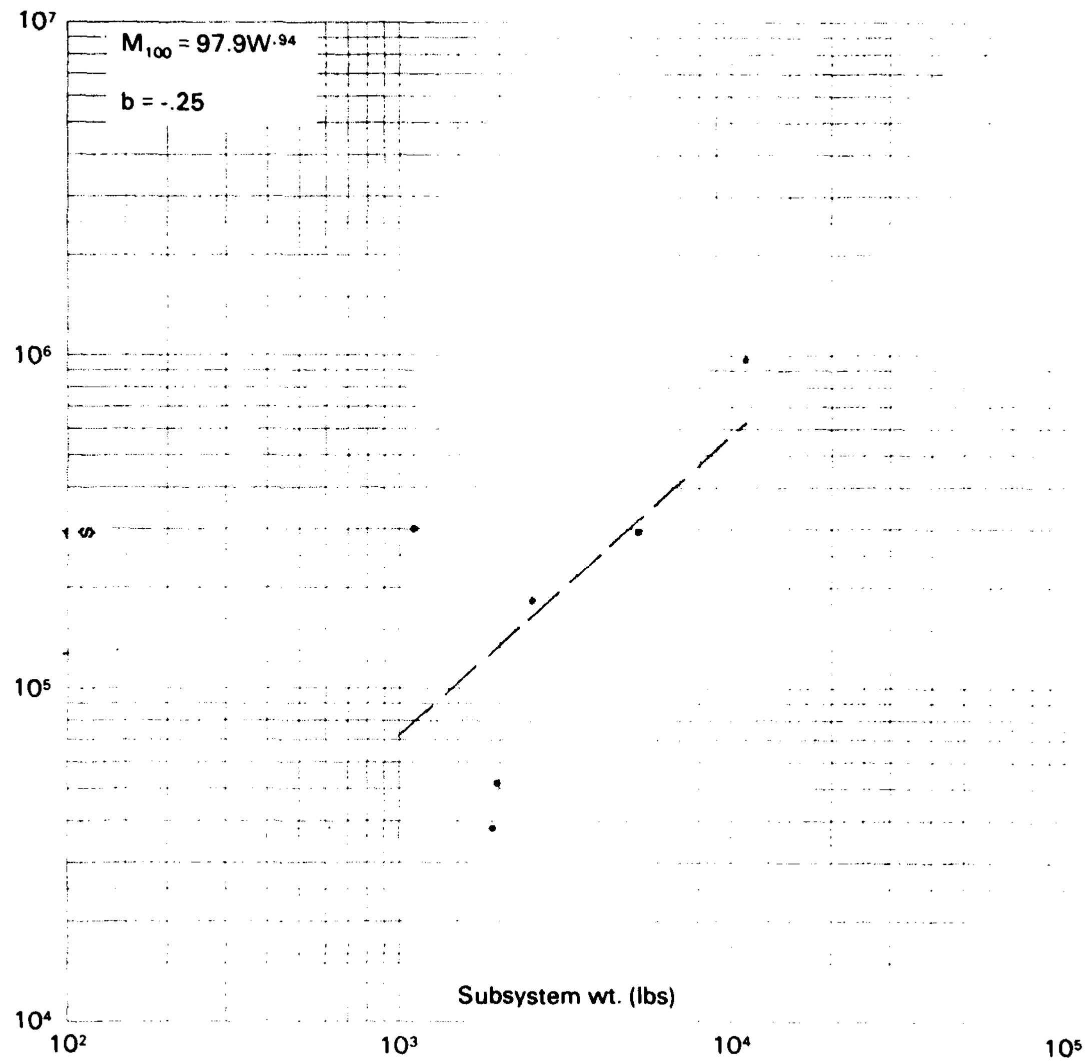

Fig. 2—Material \$* vs control/hydraulic weight

*100th unit cum ave value

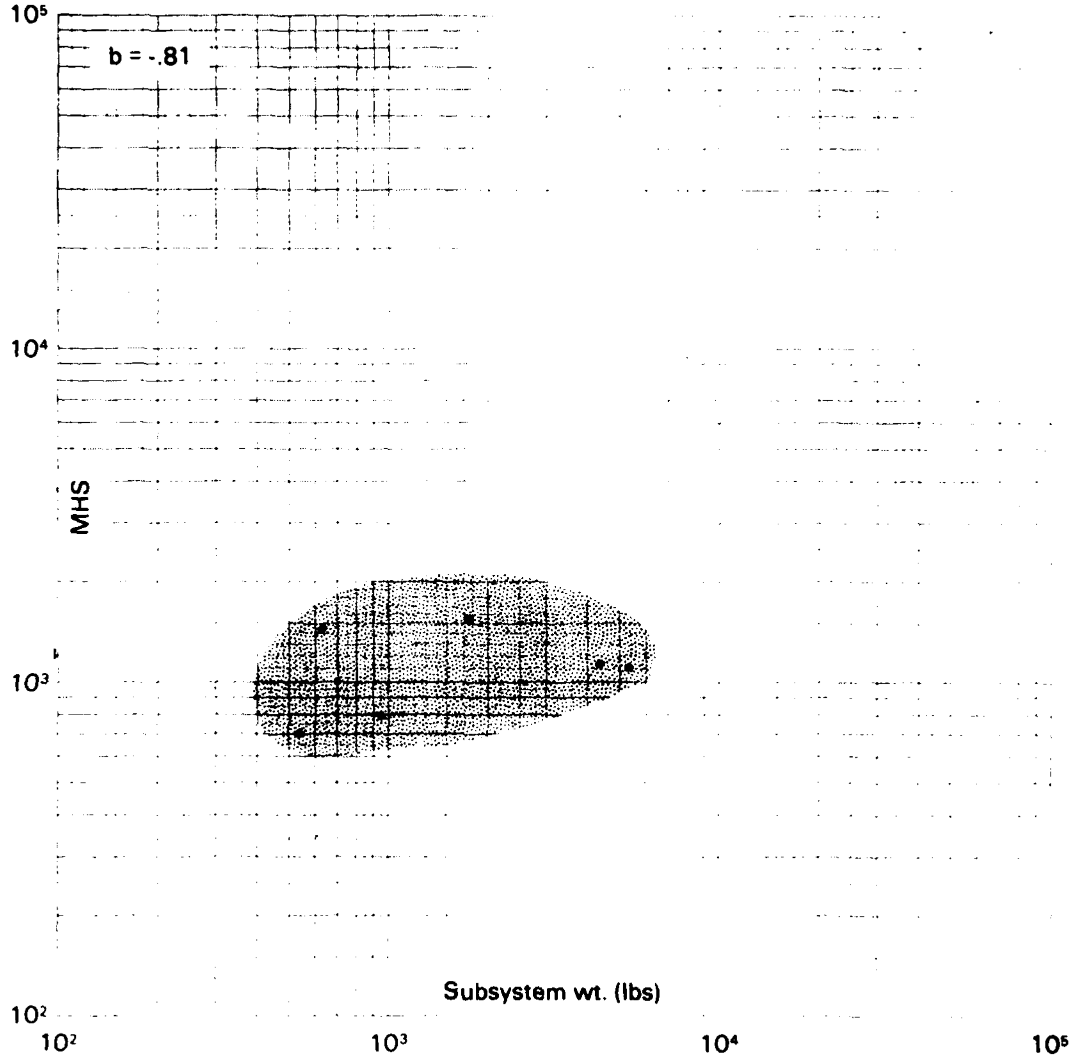

Fig. 3—Tooling MHS* vs electrical system weight

*100th unit cum ave value

Table 4

SUMMARY OF ESTIMATING METHODS

	Engineering		Tooling		Manufacturing		Material	
Aircraft Group	E	P	E	P	E	P	E	P
Wing	x		x		x		x	
Fuselage	x		x		x		x	
Forward fuselage		x	x		x			x
Mid fuselage		x	x		x		x	
Aft fuselage		x	x		x		x	
Empennage	x		x		x		x	
Landing gear		x	x			x	x	
Electrical		x		x	x		x	
Controls and hydraulics	x		x		x		x	
Furnishings and equipment	x		x		x		x	
Environmental controls	x		x			x		x
Propulsion total	x			x	x		x	
Fuel system	x			x		x		x
Propulsion system	x			x	x		x	
Avionics		x		x		x		x
System integration		x		x		x	x	

E = equation; P = plot.

quantity factor, b, is also shown with each equation and allows for adjusting to alternative quantities.[2]

[2] The cost-quantity factor, b, was derived from mean cumulative average values for the 1st, 50th, and 100th units and can be used to estimate the cumulative average value for any quantity based on the following relationship:

$$Y = A_1 X^b$$

where

Y = the cumulative average hours or cost for quantity X.
A_1 = the hours or cost for the first unit.
X = the desired quantity.
b = the cost-quantity factor.

In the engineering, tooling, production, and materials sections that follow, the B-52 ECP-1581, the C-5A wing modification, the C-141 fuselage stretch, and the EF-111 conversion will be used as test cases for examining our initial hypothesis that the equations developed within this study can be used to estimate aircraft modification costs.

III. ENGINEERING

ENGINEERING HOURS

Engineering refers to engineering hours expended by the prime contractor in developing and producing the basic airframe.[1] More specifically, it includes engineering for (1) design, consisting of studies, stress analysis, aerodynamics, weight and balance analyses, and integration; (2) wind-tunnel models and mockups; (3) laboratory testing of components, subsystems, and static and fatigue articles; and (4) preparation, release, and maintenance of drawings, and process and materials specifications. Engineering hours not directly attributable to the airframe itself--those charged to flight testing, ground handling equipment, spares, and training equipment--are not included. Engineering hours expended as part of the tool and production-planning function are included with the cost element tooling (see Sec. IV).

For each group the intent was to derive estimating relationships based on the data collected. Because of the small sample sizes and extreme scatter encountered in the data, it was possible to derive only six equations using regression analysis. Where discernible trends existed, a line was visually fitted to the plotted data and an equation was derived. Four equations were developed using this visual method. Six groups revealed no trends from their plotted data and a shaded region was drawn around the points.

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[1] If subcontracted, the engineering hours for a particular group should also be included.

Table 5 displays the results of the analysis of engineering hour data. Weight, the predominant independent variable, appears in each of the equations derived using regression analysis. The combination of aircraft speed and weight variables appears only in the fuselage equation. The weight exponent varies from 0.42 for the controls/hydraulics group to 0.83 for the empennage. Finally, the cost-quantity factor, b, exhibits little variability.[2]

Figure 4 shows an hours vs weight plot for the groups for which regression equations could be obtained. Figure 5 displays a similar plot for the equations derived by visual means. However, any engineering estimates obtained from the equations in Table 5 represent only a first step because secondary development (modification) typically requires many fewer hours than original development. According to industry sources, it is easier to make a change to a previously designed item than it is to design and develop the item in the first place. For example, Douglas Aircraft Company's experience on DC-8 modifications suggests that design engineering on a modification program ranges from about 30 to 60 percent of original development in terms of the hours per pound for a given cost weight:[3]

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[2] b = (log learning)/(log 2). This equation shows that for a value of L = 55.4 percent, the corresponding value of b is (log.55)/(log 2) or -.85.

[3] "Cost weight" is not synonymous with "new weight." Excluded from cost weight are major purchased parts or parts for which the weight involved in a change is disproportionately high relative to the engineering required.

Table 5

ENGINEERING ESTIMATING EQUATIONS

(100th unit cumulative average manhours)

Group	Estimating Relationship	Type of Derivation	Observations	Statistics R^2	Statistics Mean	Statistics SEE[a]	Cost-Quantity Factor b	Cost-Quantity Factor L(%)	Range of Independent Variable (lb)
Wing	$E_{100} = 54.89\ W^{.50}$	Regression	9	.83	9.02	.30	-.85	55	3,700 - 82,000
Fuselage	$E_{100} = .0005\ S^{1.29} W^{.95}$	Regression	12	.73	9.21	.65	-.88	54	3,200 - 116,000
Forward fuselage[b]	See plot in App. B	--	6	--	--	--	-.84	56	760 - 2,500
Mid fuselage[b]	See plot in App. B	--	4	--	--	--	-.86	55	1,500 - 6,300
Aft fuselage	See plot in App. B	--	7	--	--	--	-.87	55	490 - 3,000
Empennage	$E_{100} = 4.57\ W^{.83}$	Regression	8	.84	7.76	.40	-.85	55	600 - 12,000
Landing gear	See plot in App. B	--	12	--	--	--	-.82	57	600 - 28,000
Electrical	$E_{100} = 21.4\ W^{.71}$	Visual	9	--	--	--	-.79	58	380 - 2,000
Controls/hydraulics	$E_{100} = 235.68\ W^{.42}$	Regression	12	.54	8.75	.35	-.84	56	1,100 - 16,500
Furnishings/equipment	$E_{100} = 85.3\ W^{.45}$	Visual	8	--	--	--	-.88	54	300 - 6,900
Environmental controls	$E_{100} = 47.1\ W^{.63}$	Visual	8	--	--	--	-.83	56	180 - 3,600
Propulsion total	$E_{100} = 138.17\ W^{.50}$	Regression	9	.69	8.71	.44	-.84	56	470 - 16,000
Fuel system	$E_{100} = 16.98\ W^{.75}$	Regression	6	.72	7.83	.63	-.84	56	300 - 7,000
Propulsion system	$E_{100} = 15.5\ W^{.75}$	Visual	5	--	--	--	-.85	55	180 - 2,800
Avionics	See plot in App. B	--	7	--	--	--	-.86	55	30 - 3,800
System integration	See plot in App. B	--	5	--	--	--	-.69	62	9,000 - 283,000

[a]SEE = the standard error of estimate, which is given in logarithmic form, may be converted into a percentage of the corresponding hour or dollar value by performing the following calculations: $e^{+SEE} -1$; $e^{-SEE} -1$. For example, a standard error of $\pm$ .30 yields standard error percentages of +35 and -26. The mean, which is the mean value of manhours through the 100th unit, is also shown in logarithmic form.

[b]Sample consists of fighter and attack aircraft.

-- Not applicable.

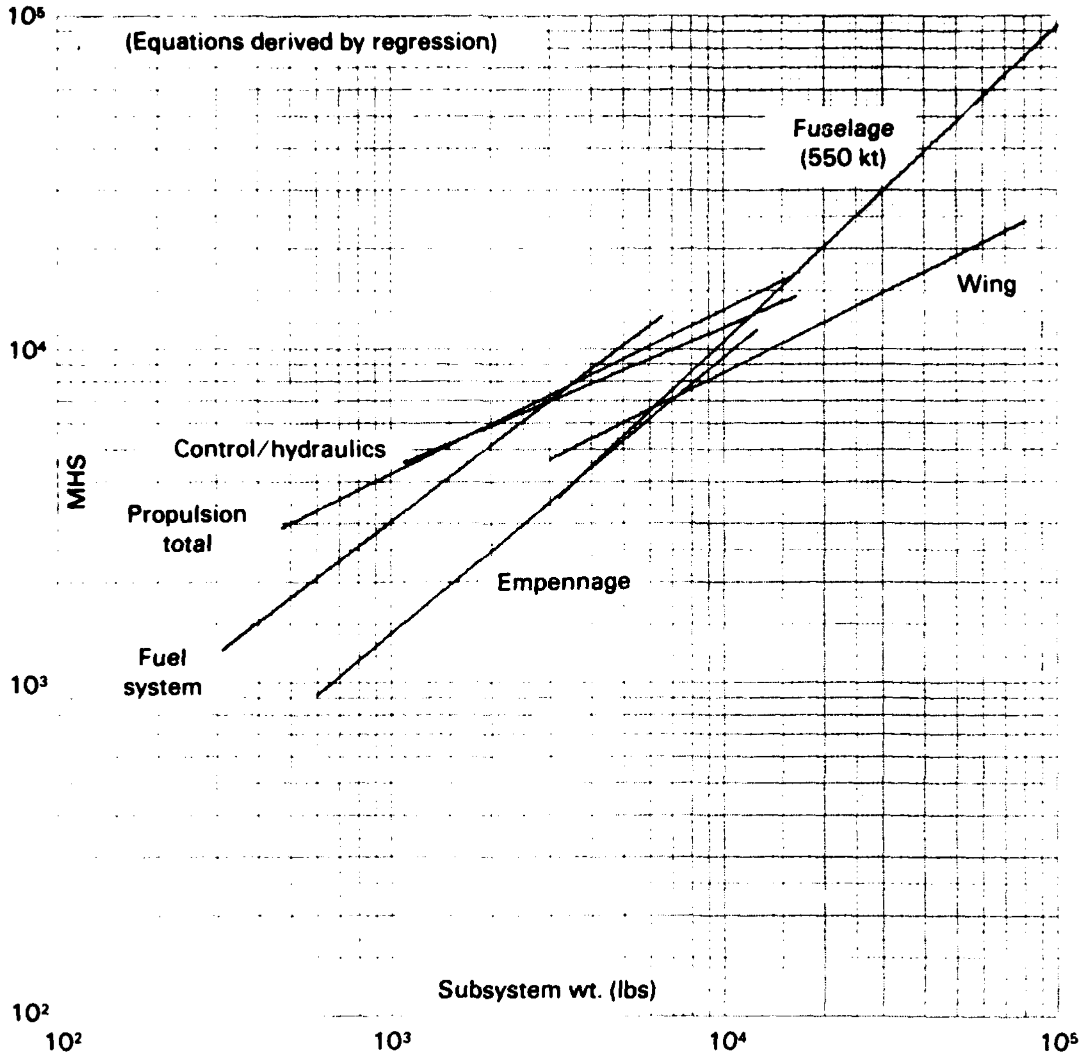

Fig. 4—Engineering MHS* vs group weight

*100th unit cum ave value

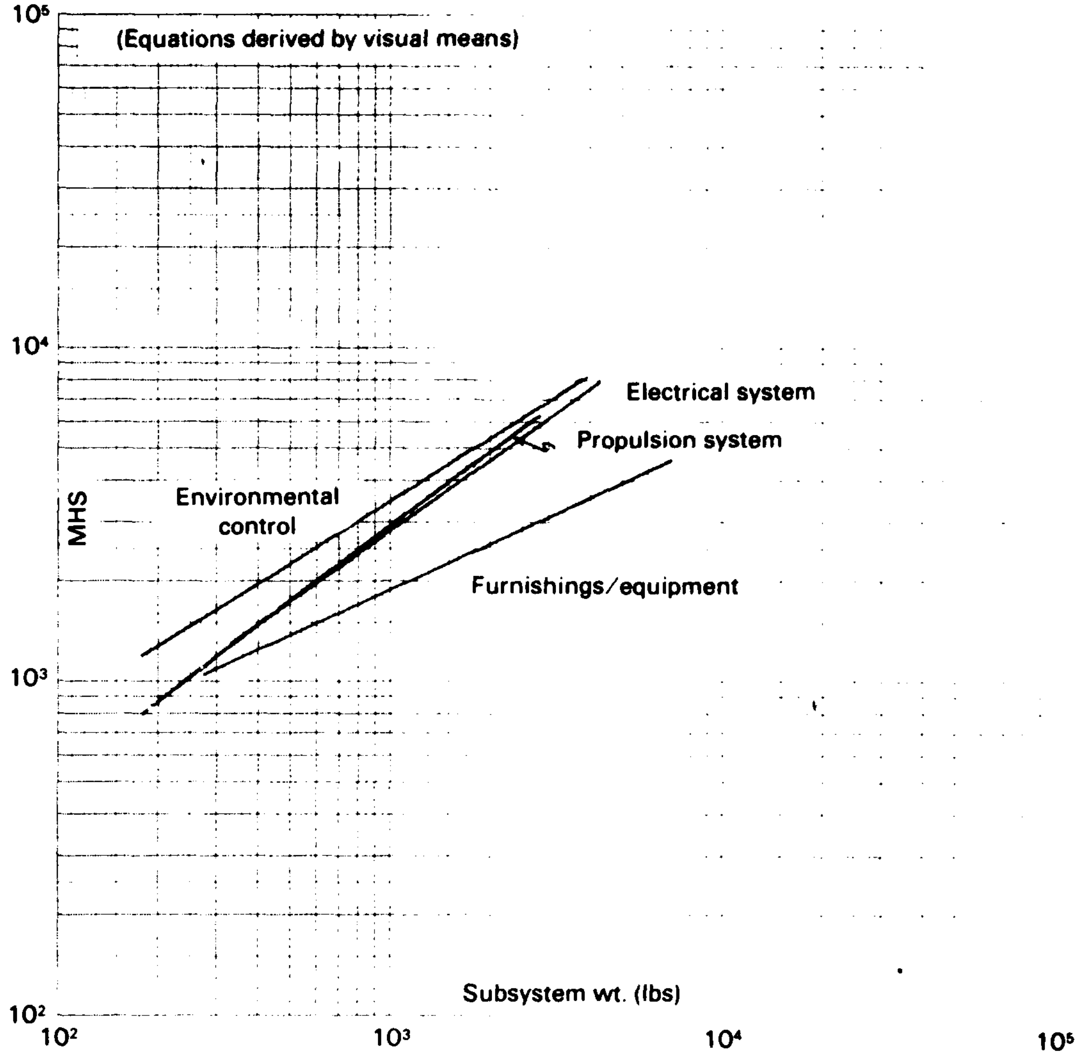

Fig. 5—Engineering MHS* vs group weight

*100th unit cum ave value

	Percent of Original Engineering Hours
DC-8F. Change to a convertible cargo/passenger version. Bulkhead between freight and passenger compartments is movable; hold has provision for mechanized loading of pallets--changes have high weight relative to engineering required.	30.9
DC-8 Series 61. Fuselage extended by placing 20 ft cabin section forward of wing and 16 ft 8 in. section aft of wing.	40.9
DC-9 Series 40. Increased fuel capacity. Extended fuselage.	47.2
DC-8 Series 50. Change to JT3D fanjet engine. Installation of new wing leading edge.	53.7
DC-9 Series 30. Increased wing span. Extended fuselage. New high-lift devices including full-span leading edge slats and double-slotted flaps.	56.7
DC-8 Series 62. Fuselage extended by placing 3 ft 4 in. section forward and aft of wing. New engine pods and pylons. Extended wingtips.	60.4

The changes above were not modifications to a fleet of aircraft that had been in service in a variety of environmental and operating conditions. They were the changes required to produce a new series of aircraft, hence do not include the increased installation engineering inherent in a mod program. Also, design engineering in some cases accounts for less than half of all nonrecurring engineering. Development and system test, system engineering and program management constituted 34-67 percent of nonrecurring engineering hours in a sample of 16 development programs (Table 6) with a mean of about 50 percent. When

that range is combined with the Douglas numbers, it suggests that nonrecurring engineering hours per pound in a mod program can run from less than 50 percent to almost 100 percent of new development engineering. The extremes are characterized as follows:

Less than 50%--A modification where the new weight is high relative to the complexity of the change (e.g., increasing the gauge of wing skins or floors), testing is minimal, and little system integration is involved.

Almost 100%--A modification with little new structural weight but requiring extensive integration and testing.

The range is broad and leaves considerable margin for error, but as more becomes known about a proposed modification it should be possible to narrow that range.

For nonrecurring engineering hours our hypothesis is that modification estimates require a factor be applied to the E_1 value, Unit 1

Table 6

DESIGN ENGINEERING AS A PERCENTAGE OF TOTAL NONRECURRING ENGINEERING HOURS

Aircraft	Percent	Aircraft	Percent
E-2C	34	C-141A	55
F-18A	36	A-5A	56
F-15A	38	A-6A	59
C-5A	41	B-52/A/B	60
S-3A	43	F-4A	60
T-38A	43	A-10A	63
EA-6B	44	L-1011	65
F-14A	52	P-3C	67

Engineering Hours. Available data suggest that a factor between 0.5 and 1.0 would be appropriate; however, each modification would require a different factor. To test the hypothesis a 0.75 factor is used initially.

RECURRING ENGINEERING

In calculating recurring engineering hours we recommend using the b value shown in Table 5 and in the upper left corner of the plots in App. B. This b value, or cost-quantity factor, was calculated based on a curve fitted to the 1st, 50th, and 100th cumulative average values for each group. Unit 1 engineering hours represent the nonrecurring component, and all subsequent hours are considered recurring. For example, with Table 5, a wing modification involving 5000 lb of new weight would require the following steps to arrive at an estimate of hours:

$$E_{100} = 84.89(5{,}000)^{.50}$$

$$= 6{,}003 \text{ hr}$$

$$6003 = E_1(100)^{-.85}$$

$$E_1 = 300{,}863 \text{ hr}$$

$$E_x = 300{,}863X^{-.85}$$

where E_x = cumulative average engineering hours for X aircraft (includes recurring and nonrecurring).

With such equations, total program hours can be estimated for any quantity of aircraft The b value is associated with a 55 percent slope, which is representative of new development programs. Steeper slopes are often said to be a characteristic of modification programs, but estima-

tors must be cautious in accepting such generalizations because a few percentage points can make a substantial difference in total recurring hours. In the equation above when the exponent is changed from -.85 to -.92 (a 53 percent curve), the recurring cost for 100 units decreases by 28 percent. Based on the data available we believe that a 55-56 percent curve is reasonable for most mod programs; variations from that would have to be justified by the characteristics of a particular program.

TEST CASES

B-52 ECP-1581

The Wichita Division of the Boeing Aircraft Company modified 80 B-52s during 1974 and 1975 in an extensive program that included removing the wings, replacing leading edge skins and certain body skins, redesigning fairings, changing the wiring in the wing, and a number of other improvements. Collectively, the modifications are known as ECP 1581 (see Table 7 for weights).

Using the parametric equations listed in Table 5 and the .75 adjustment factor, we estimated the engineering hours required for the modification program. The estimate of nonrecurring hours was much greater than those actually experienced. To make a good estimate we would have had to evaluate the modification as being at the low end of the range discussed above--about 30 percent of original design hours. The predicted recurring engineering hour curve--55 percent--is two percentage points higher than the curve experienced.

Table 7

ECP 1581 WEIGHT STATEMENT

Boeing Weight Statement Group	Cost Group	New Weight (lb)
Wing box Leading edge Outboard wing Inboard wing Outer wing	Wing	26,358
Fuselage	Fuselage	3,288
Propulsion	Propulsion system	130
Airframe systems	Controls/ hydraulics	2,341
TOTAL		32,117

C-5A Wing Modification

The proposed C-5A wing modification involves approximately 75,000 lb of new weight excluding sealants, interior and exterior finishes, and all salvaged items. About 69,000 lb is for wing structure; the remainder is for flight control, hydraulics, electrical, and others. The weights and aircraft groupings used are shown in Table 8.

Actual nonrecurring engineering hours, estimated by Lockheed-Georgia, amount to approximately two-thirds of the Rand estimate. Given the complexity of the mod one might have expected a higher factor, but a spokesman for Lockheed-Georgia explains that much of the necessary

Table 8

C-5A WING MODIFICATION WEIGHT STATEMENT

Lockheed Weight Statement Group	Cost Group	New Weight (lb)
Center wing box	Wing	10,913
Inner wing	Wing	37,559
Outer wing	Wing	20,573
Controls	Controls/ hydraulics	1,676
Hydraulic	Controls/ hydraulics	583
Fuel system	Fuel system	1,834
Electrical	Electrical	721
Fire prevention Instrument installations Electronic installations Air conditioning/ de-icing	Furnishings/ equipment	505
Fuselage structure	Fuselage	1,196
TOTAL		75,560

engineering analysis was performed under the C-5 production program because of problems discovered during fatigue testing at that time. If those hours were charged to the mod program, the total would be considerably higher.

The lower number of nonrecurring hours has an effect on the slope of the recurring hour curve; starting from a lower point will give a flatter curve if recurring hours are unchanged. Actually, recurring

engineering is expected to be somewhat higher than normal because of increased fracture and fatigue-critical requirements. Those two factors contribute to the current predicted slope of 59.3 percent versus a Rand estimate of 56 percent. The result is that the Rand estimate of total engineering hours would be slightly higher at 100 units and slightly lower at 200 units.

C-141 Fuselage Stretch

Lockheed-Georgia has stretched the fuselage of the C-141A by inserting plugs fore and aft of the wing, and that modification affects a variety of aircraft groups as well as the fuselage. The modification also includes an inflight-refueling provision. The new weights involved for each group are shown in Table 9

With the Rand method, nonrecurring engineering hours are almost identical to the Lockheed-Georgia estimate. In retrospect, this modification is closely analogous to the DC-8 fuselage stretch where engineering hours per pound amounted to 40 percent of original hours per pound. Applying that factor to the estimate above would result in a number slightly less than half of the actual. According to Lockheed estimators, new weight is not a good explanatory variable in this case because much of the engineering is for integration with existing structure, not designing new structure. That would be equally true for the B-52 ECP 1581 and C-5 wing mod, however. The only common thread among the three programs is that the Rand equations, unadjusted, always estimate higher than actual hours. The extent of the difference varies in each case.

Table 9

C-141 STRETCH WEIGHT STATEMENT

Lockheed Weight Statement Group	Cost Group	New Weight (lb)
Fuselage	Fuselage	6,222
Electrical	Electrical	446
Controls	Controls/ hydraulics	210
Furnishing and equipment	Furnishing/ equipment	562
Propulsion	Propulsion total	135
Environmental	Environmental controls	225
TOTAL		7,800

For recurring engineering Lockheed-Georgia predicts an unusually steep learning curve--52 percent--despite their contention that differences in individual C-141 configurations should cause an increase in installation engineering. The Rand equations predict 55 percent, which seems to us to be a more reasonable figure.

EF-111A Conversion

In the EF-111A modification program 42 F-111As are being converted to perform the tactical jamming mission. The new weights involved are shown in Table 10. A major part of the modification deals with

electronic equipment. The cost of installing that equipment is to be included but the procurement cost is not. The full-scale development program is essentially completed, but production has not begun. As a consequence, the Rand estimates cannot be compared to actual costs. In lieu of actual costs we used the September 1978 ICA as the standard against which to compare estimates.

The Air Force estimate of nonrecurring engineering hours, based on data from two prototype aircraft, was approximately one million hours; the Rand estimate was 32 percent less. This case suggests that automatically reducing the estimate (produced by the equations) may not be correct. However, if we accept the thesis that redesign is inherently

Table 10

EF-111 WEIGHT STATEMENT

Cost Group	New Weight (lb)
Empennage	1,482
Fuselage	1,792
Electrical	2,002
Furnishing/ equipment	800
Environmental controls	886
TOTAL	6,962

simpler than new design, we would not expect an estimator to use an adjustment factor greater than 1. A possible explanation for the higher unit 1 value in the EF-111A case is that the modification is not being done by the original contractor. For recurring engineering the Rand equations produce a 56 percent slope--identical to the ICA slope.[4]

SUMMARY

The data in Table 11, which compares observed hours with estimates for the four test cases, support our contention that a series of equations with simplified, straightforward inputs probably cannot provide acceptably accurate estimates of the engineering hours associated with aircraft modification programs. Conversely, if an estimator is reasonably familiar with such problems and can establish the proper adjustment factors and learning curve slopes, he can produce planning estimates that will be within acceptable limits.

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[4] Several industry estimators contend that a nominal 55-56 percent slope for this type of modification is too steep because in their experience subsystems require more sustaining engineering than structure. It remains to be seen if their position is borne out by the data when the program is finished.

Table 11

COMPARISON OF RAND METHOD WITH ACTUAL ENGINEERING HOURS[a]

Program	E_1 Adjustment Factor		Learning Curve Slope[b]		Total Hours
	Factor Required	Initial Rand Estimate	Observed	Initial Rand Estimate	Deviation Using Rand Method[c]
B-52D ECP 1581	.29	.75	.53	55	-2.20
C-5A wing mod	.50	.75	59	56	- .48
C-141 stretch	.74	.75	52	55	.38
EF-111 mod	1.11	.75	56	56	.14

[a]Where actual data are not available the latest ICA or contractor estimate was used.

[b]Learning curve slopes are composite values.

[c]$\text{Deviation} = \dfrac{\text{Total Observed Hours - Rand Estimate}}{\text{Total Observed Hours}}$

IV. TOOLING

TOOLING HOURS

Tooling refers only to the tools designed solely for use on a particular airframe program--assembly tools, dies, jigs, fixtures, work platforms, and test and checkout equipment. General-purpose tools such as milling machines, presses, routers, and lathes are considered capital equipment. Tooling hours include all effort expended in tool and production planning, design, fabrication, assembly, installation, modification, maintenance, rework, and programming and preparation of tapes for numerically controlled machines. Nonrecurring tooling refers to the initial set of tools and all duplicate tools produced to attain a specified rate of production.

Tooling hours can be related more directly to an aircraft group without the need for allocation that characterizes the other functional cost elements (see Table 12). Consequently, the data are more consistent and, as shown by Table 13, estimating equations were obtained for all of the structural groups plus several others. Figure 6 shows hours-vs-weight plots for the groups for which regression equations could be derived. Figure 7 displays similar plots for the equations derived by visual means. Weight was found to be the only useful independent variable. Production rate is a logical candidate, but neither in this study nor in others have we been able to isolate its effect on tooling hours with statistical methods. First flight date is also considered an important variable by airframe estimators, and

Table 12

ALLOCATION OF TOOLING

(Percent of tooling hours spent on Unit 1)

	A-6	A-10	B-52	C-5A	C-130A	C-141A	F-4	F-14A	F-15	F-16	KC-135
Wing	21.3	31.9	27.1	28.1	30.1	20.0	33.3	16.1	25.3	12.8	29.5
Forward fuselage	30.8		8.1				30.0	12.8	12.8	21.5	9.6
Mid fuselage	13.9	31.5	12.4	49.2	29.5	31.5	17.0	42.0	15.8	15.0	11.8
Aft fuselage	6.0		3.4				13.0	16.6	29.7	13.8	9.4
Empennage	6.0	7.1	8.0	4.6	5.6	5.00	4.5	6.8	8.0	9.7	10.3
Landing gear	0.2	—	8.3	0.9	8.5	0.3	1.3	0.2	1.0	3.6	1.2
Flight controls	—	—	—	0.7	1.0	2.6	0.1	1.6	0.4	1.5	
Hydraulic	0.5	—	—	0.2		1.2		—	—	1.8	—
Electrical	—	—	—	0.4	0.8	0.6	0.2	0.9	2.1	4.1	
Propulsion	2.5	—	—	11.6	14.5	3.6	—	0.8	—	—	
Fuel system	1.4	—	0.1	—	—		0.1	—	1.1	2.7	0.1
Avionics	1.3	—	—	0.2	0.4	0.6	—	—	—	0.9	
ECS	0.8	—	—	1.0	1.3	1.1	—	—	—	2.3	
Furnishings and equipment	—	—	—	1.3	2.4	2.0	0.1	0.5	1.7	—	
Integration	10.7	12.1	—	2.3	6.0	4.8	—	1.0	—	3.9	

[a]Percentages do not necessarily total to 100 percent.
— Not applicable.

Table 13

TOOLING ESTIMATING EQUATIONS

(100th unit cumulative average manhours)

Group	Estimating Relationship	Type of Derivation	Observations	Statistics R^2	Statistics Mean	Statistics SEE	Cost-Quantity Factor b	Cost-Quantity Factor L(%)	Range of Independent Variable (lb)
Wing	$T_{100} = 48.62\ W^{.70}$	Regression	10	.76	10.17	.50	-.83	56	3,000 - 82,000
Fuselage	$T_{100} = 193.68\ W^{.59}$	Regression	10	.76	10.81	.37	-.82	57	3,500 - 116,000
Forward fuselage	$T_{100} = 4.03\ W^{1.06}$	Regression	7	.96	10.08	.16	-.84	56	800 - 6,000
Mid fuselage	$T_{100} = 7.60\ W^{.92}$	Regression	8	.75	9.41	.49	-.84	56	1,300 - 14,000
Aft fuselage	$T_{100} = 25.66\ W^{.80}$	Regression	9	.81	8.98	.39	-.84	56	500 - 6,000
Empennage	$T_{100} = 28.53\ W^{.73}$	Regression	9	.85	7.74	.35	-.82	57	600 - 12,000
Landing gear	$T_{100} = 24.2\ W^{.51}$	Visual	11	--	--	--	-.76	59	600 - 28,000
Electrical	See plot in App. B	--	6	--	--	--	-.81	57	500 - 4,400
Controls/hydraulics	$T_{100} = 6.32\ W^{.75}$	Regression	7	.59	7.25	.80	-.76	59	300 - 11,000
Furnishings/equipment	$T_{100} = 1.2\ W^{.94}$	Visual	7	--	--	--	-.81	57	270 - 6,800
Environmental controls	$T_{100} = 16.77\ W^{.64}$	Regression	6	.95	7.15	.20	-.78	58	180 - 3,600
Propulsion total	See plot in App. B	--	10	--	--	--	-.78	58	470 - 16,000
Fuel system	See plot in App. 3	--	6	--	--	--	-.79	58	300 - 7,000
Propulsion system	See plot in App. B	--	5	--	--	--	-.85	55	150 - 1,300
Avionics	See plot in App. B	--	6	--	--	--	-.76	59	30 - 5,000
System integration	See plot in App. B	--	7	--	--	--	-.79	58	9,000 - 283,000

-- Not applicable.

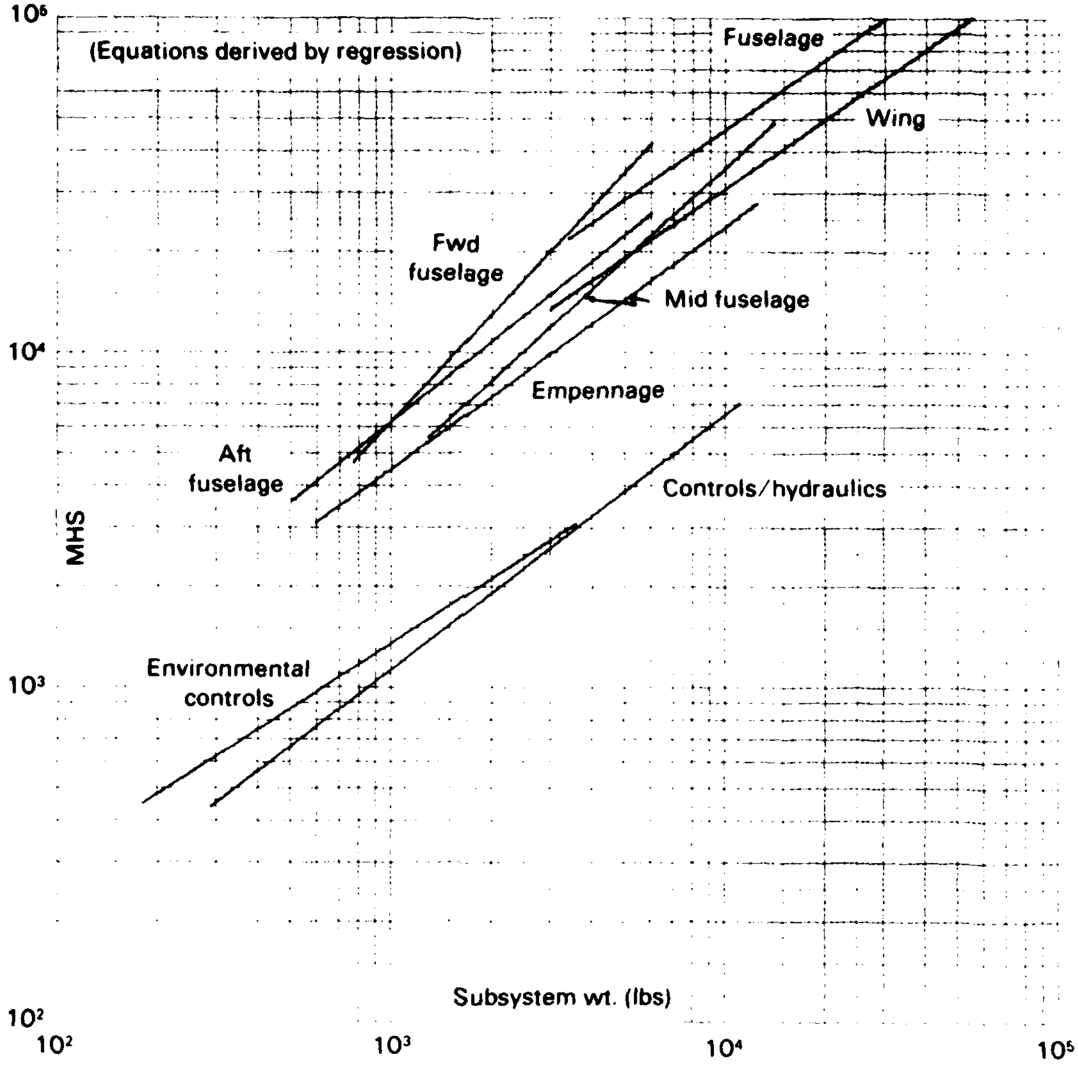

Fig. 6—Tooling MHS* vs group weight

*100th unit cum ave value

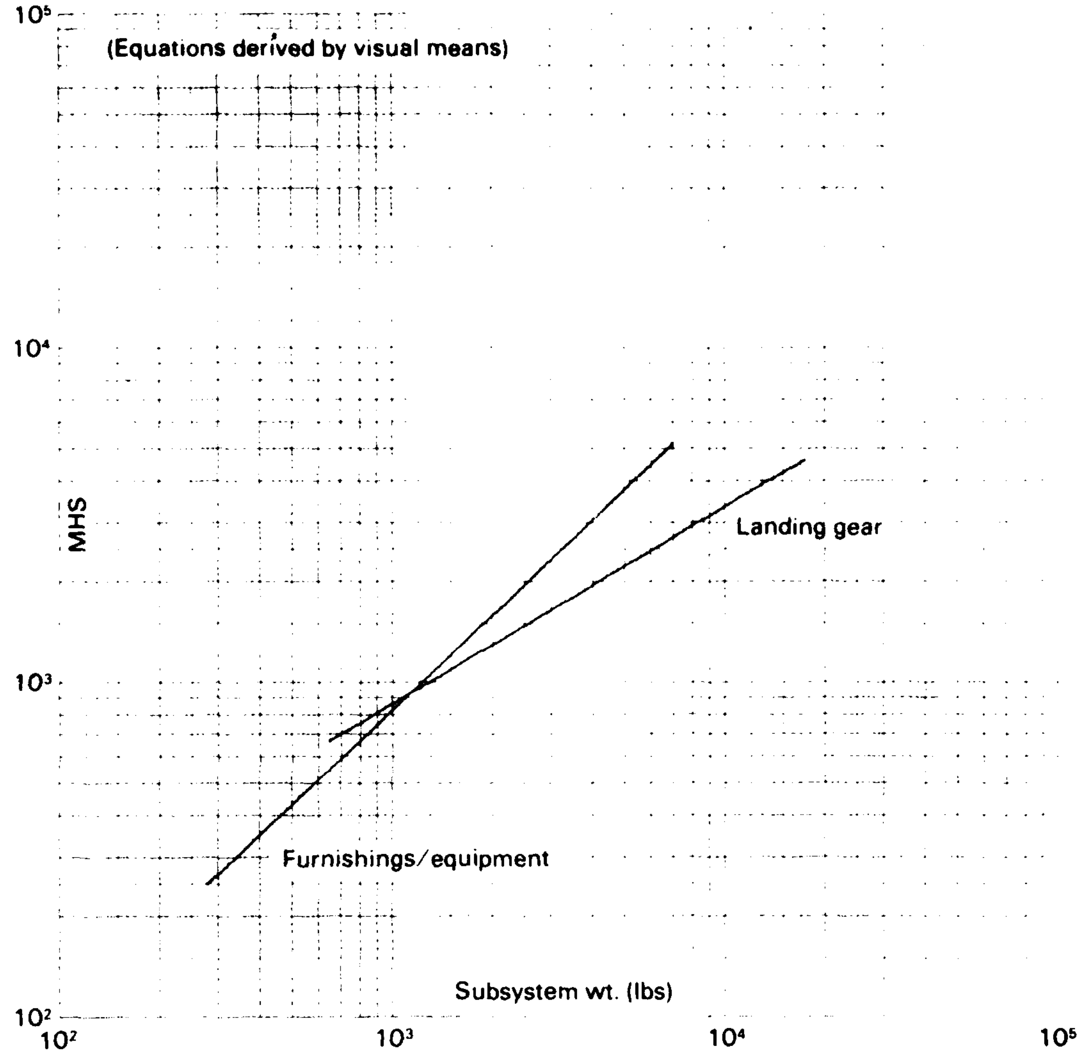

Fig. 7—Tooling MHS* vs group weight

*100th unit cum ave value

it was a statistically significant variable in several of the structural groups. Its contribution to the goodness of fit was small, however, and it was not used because of the undesirability of having two variables with sample sizes of 10 or less. The sign of the time-exponent was always negative, thus implying that tooling hours have decreased over time.

Estimating tooling hours requires more than a set of equations; it requires a knowledge of what tooling is needed and what is available. The first point impinges on the value of new weight as an independent variable. Putting a plug in the fuselage of a cargo aircraft, for example, requires tooling fixtures to hold both new and old structures; the latter will not be included in an estimate based on new weight. Offsetting that problem in some cases will be the availability of tooling remaining from the original production program. C-5A tooling was stored at Lockheed-Georgia and at AVCO (subcontractor for the wing), so little new tooling will be required for the C-5A wing modification program. Use of the wing equations from Table 13, with new weight as the independent variable, would greatly overstate tooling hours in that program.

With inheritance it is difficult to assess how much tooling is usable for a particular modification against how much new tooling must be produced. We have no empirical basis for making such a determination. However, as an initial hypothesis we will assume that 50 percent would be inherited, unless it is known that the old tooling was destroyed. In the four cases to be tested, the last two are known to require nearly all new tooling.

RECURRING TOOLING

Learning curves for tooling calculated using the equations in Table 13 are steep for most structural groups--about 56-57 percent--and should be applicable to modification programs.[1] The T_1 value must include an allowance for inherited tools, however, or the estimate of recurring hours will be too low.[2] Dealing with inherited tooling poses an additional problem when estimating recurring hours because previous quantities probably should be taken into account. For example, if a total of 100 aircraft were produced and subsequently were returned for modification, recurring tooling associated with the inherited tools would be based on 100 modified aircraft following the original 100. Thus, recurring tooling should be separated into two categories--one stemming from the applicable original tooling, the other based on new tooling required for the modification.

TEST CASES

B-52 ECP 1581

The Rand equations estimate a requirement for 3.8 million nonrecurring tooling hours, but as mentioned above, that assumes that no tooling is available. Companies tend to keep tools almost indefinitely and before destroying them must have the permission of the Air Force or Navy. Without information to the contrary, we would assume that much

[1] If the numbers of aircraft involved are small, the effort made to maintain tooling appears to be minimal. The philosophy seems to be that if it looks as if a tool won't hold up, maintenance is postponed in the hope that it will last as long as needed.

[2] See the tooling section of the example calculation in App. A.

tooling has been stored and the tooling hours required will be only a fraction of the original. In the case of ECP 1581 actual hours were approximately 35 percent of our unadjusted estimate. Recurring tooling hours reported by Boeing imply a much steeper learning curve than we predict--52 percent rather than 56 percent--based on new tooling only. The actual learning curve would be even steeper than 52 percent with inherited tools included.

C-5A Wing Mod

Nonrecurring tooling hours estimated by Lockheed-Georgia on the C-5A wing mod are lower than our equations predict because tools exist both at the Lockheed-Georgia and AVCO subcontractor production facilities. The Lockheed-Georgia estimate is only about 14 percent of the unadjusted Rand number. With sufficient knowledge about the availability of tool inheritance, an estimator could adjust his estimate accordingly. Further, to estimate recurring tooling hours, he could have used the 14 percent figure to derive an estimate of inherited tooling. With such data, plus the fact that 81 aircraft had previously been produced, he would have obtained an estimate approximately 8 percent different from the Lockheed-Georgia number.

C-141 Fuselage Stretch

Assembly and installation tools for the C-141 had been disposed of between the end of the production run and the time the fuselage-stretch program was proposed.[3] With little original tooling available plus the

[3] Certain C-141A spares tooling is available and will be used on the stretch modification.

fact that the major portion of the C-141 mod is for structure that did not exist previously, we have a good opportunity to test the Rand T_1 value. The Rand equations generate an estimate 15 percent higher than the contractor's estimate, and 5 percent lower than the Air Force ICA. Lockheed-Georgia estimators believe the ICA figure is too high, but the Rand estimate appears to be reasonable.

In this case we can assume that the above estimate includes all nonrecurring tooling; it is a valid basis to use in estimating recurring hours. Lockheed-Georgia and Air Force estimates of recurring tooling hours are made in different ways, but in both the result is the same as would be obtained by assuming a 53.5 percent learning curve. Although not as steep as noted in the B-52 mod, the curve is steeper than that found in original production. Recurring hour estimates are very sensitive to small changes in slope when the curve is that steep. For 272 aircraft a 53.5 percent curve produces a recurring cost estimate 25 percent higher than a 52 percent curve. One factor influencing choice of slope is the probability that all aircraft will have identical configurations. Variations in configuration increase recurring tooling hours because additional planning is required. It is assumed by Lockheed-Georgia that such planning will be needed on the C-141 mod.

EF-111A

Tooling on the EF-111A is not expected to be extensive because little structural change is involved. The tools are all new and the mod is not being done by the original producer, so the Rand equations should be directly applicable. The Rand estimate for nonrecurring tooling is 2

percent higher than the Grumman estimate, and the ICA estimate is slightly lower than Grumman's. We have no information that would justify modifying our estimate, and we believe it is reasonable for the purposes involved.

Recurring tooling hours were apparently estimated by Grumman on a 56 percent curve. Use of the Rand equations would give a 57 percent slope, but we have seen in the three previous examples that steeper tooling hour slopes appear to be characteristic of modification programs. The ICA estimate was calculated in a different way--recurring hours = 1 percent of nonrecurring hours per month of mod program--and is equivalent to assuming a 53.6 percent curve. The difference cannot be resolved at this time, but we are inclined to choose the steeper curve for planning purposes.

SUMMARY

Tooling estimates depend critically on the tools available from previous production. Where new tools are required, the Rand equations appear to give reasonable estimates of nonrecurring tooling hours (see Table 14). When previously built tools are available, the estimate must be adjusted to take that availability into account.

Recurring tooling hours are only a fraction of those experienced in production programs. For estimating purposes, that implies steeper learning curves--52 to 54 percent--when nonrecurring hours are based on a requirement for new tools. Those slopes will not apply when previously built tools are available.

Table 14

COMPARISON OF RAND METHOD WITH ACTUAL TOOLING HOURS[a]

Program	T_1 Adjustment Factor		Learning Curve Slope[b]		Total Hours
	actor Required	Initial Rand Estimate	Observed	Initial Rand Estimate	Deviation Using Rand Method[c]
B-52 ECP 158	.34	[illegible]	52	56	-1.47
C-5A wing mod	.14	[illegible]	60	56	-1.54
C-141 stretch	.87	1.00	64	56	-.65
EF-111 mod	.90	1.00	56	57	-.21

[a] Where actual data are not available the latest ICA or contractor estimate was used.

[b] Learning curve slopes are composite values and for new tooling only.

[c] $\text{Deviation} = \dfrac{\text{Total Observed Hours} - \text{Rand Estimate}}{\text{Total Observed Hours}}$

V. PRODUCTION

RECURRING PRODUCTION HOURS

Production hours include all recurring direct labor necessary to machine, process, fabricate, and assemble the major structure of an aircraft and to install purchased parts and equipment, engines, avionics, and ordnance items, whether contractor-furnished or government-furnished. Also included is the labor component of off-site manufactured assemblies or certain parts that are design-controlled for the basic aircraft, because of their configuration or other characteristics. Such assemblies can represent a substantial part of the manufacturing effort and are included regardless of their method of acquisition. Examples of such parts are actuating hydraulic cylinders, radomes, canopies, ducts, passenger and crew seats, and fixed external tanks. Hours required to fabricate standard purchased parts and materials are excluded from this cost element.

Production hours generally constitute the largest component of cost (when burden is added) and the most important to estimate correctly. Unfortunately, the large amount of subcontracting characteristic of aircraft production makes it difficult to compile a homogeneous set of costs by aircraft group that contains both inplant and outside production hours. The lack of comparability in the data shows up mainly in nonstructural groups, as shown by Tables 15 and 16. No regression-supported equations could be developed for those groups. Figures 8 and

Table 15

ALLOCATION OF PRODUCTION[a]

(Percent of engineering hours spent on Unit 1)

Item	A-6	A-10	B-52	C-5A	C-130A	C-141A	F-4[b]	F-14A	F-15	F-16	KC-135
Wing	12.9	28.7	16.8	18.2	25.8	25.3	5.1	11.8	11.2	10.5	30.7
Forward fuselage	12.4		5.4			7.2	4.0	11.1	6.1	18.8	9.1
Mid fuselage	8.0	38.7	10.5	48.9	38.5	6.1	1.7	24.6	25.4	13.3	12.2
Aft fuselage	2.4		1.6			16.2	1.0	13.7	24.0	8.6	8.2
Empennage	2.5	5.4	3.6	2.7	8.3	6.7	1.2	5.0	5.0	5.5	5.3
Landing gear	1.6	9.5	0.0	5.6	2.0	0.4	17.6	1.3	1.8	1.6	0.2
Flight controls	--	--	--	2.1	2.2	2.8	1.3	3.8	13.6	2.8	--
Hydraulic	4.2	--	--	1.0	1.1	2.1		--		1.2	--
Propulsion	1.1	--	--	6.5	6.9	12.8	--	2.1	--	--	--
Fuel system	--	--	1.7	--		0.7	1.1	--	2.8	2.3	0.2
Electrical	--	--	--	2.5	6.2	4.6	12.2	3.5	2.4	8.0	--
Avionics	--	--	--	6.6	1.2	1.7	--	--	--	2.9	--
Environmental control systems	--	--	--	1.2	1.6	0.9	--	--	--	1.5	--
Furnishings and equipment	--	--	--	2.0	4.4	3.1	7.1	1.0	4.1	--	--
Integration	73.2	17.7	--	4.5	2.7	8.6	--	20.4	--	19.9	--

[a]Percentages do not necessarily total 100 percent.

[b]Final assembly reported as 47.6 percent.

-- Not applicable.

Table 16

PRODUCTION HOUR EQUATIONS

(100th unit cumulative average manhours)

Group	Estimating Relationship	Derivation	Observations	Statistics			Cost-Quantity Factor		Range of Independent Variable (lb)
				R^2	Mean	SEE	b	L(%)	
Wing	$P_{100} = 32.1\ W^{.77}$	Regression	13	.88	10.38	.37	-.38	77	1,800 - 82,000
Fuselage	$P_{100} = 32.9\ W^{.83}$	Regression	13	.71	11.00	.58	-.38	77	3,200 - 116,000
Forward fuselage	$P_{100} = 42.5\ W^{.79}$	Regression	9	.60	9.71	.43	-.33	79	800 - 6,000
Mid fuselage	$P_{100} = 55.0\ W^{.74}$	Regression	7	.83	10.16	.31	-.38	77	1,300 - 14,000
Aft fuselage	$P_{100} = 15.57\ W^{.92}$	Regression	8	.82	9.80	.42	-.39	76	560 - 7,000
Empennage	$P_{100} = 30.0\ W^{.77}$	Regression	12	.71	8.99	.51	-.35	79	620 - 12,000
Landing gear	See plot in App. B	--	12	--	--	--	-.40	76	650 - 28,000
Electrical	$P_{100} = 26.9\ W^{.68}$	Visual	7	--	--	--	-.39	76	540 - 5,300
Controls/hydraulics	$P_{100} = 17.4\ W^{.81}$	Visual	7	--	--	--	-.38	77	300 - 11,000
Furnishings/equipment	$P_{100} = 29.8\ W^{.71}$	Visual	7	--	--	--	-.48	72	300 - 7,000
Environmental controls	See plot in App. B	--	5	--	--	--	-.36	78	200 - 3,600
Propulsion total	$P_{100} = 39.9\ W^{.67}$	Visual	10	--	--	--	-.36	78	450 - 16,500
Fuel system	See plot in App. B	--	6	--	--	--	-.36	78	300 - 6,700
Propulsion system	$P_{100} = 13.8\ W^{.76}$	Visual	7	--	--	--	-.30	81	150 - 8,000
Avionics	See plot in App. B	--	5	--	--	--	-.36	78	30 - 5,000
System integration	See plot in App. B	--	10	--	--	--	-.42	75	9,000 - 283,000

-- Not applicable.

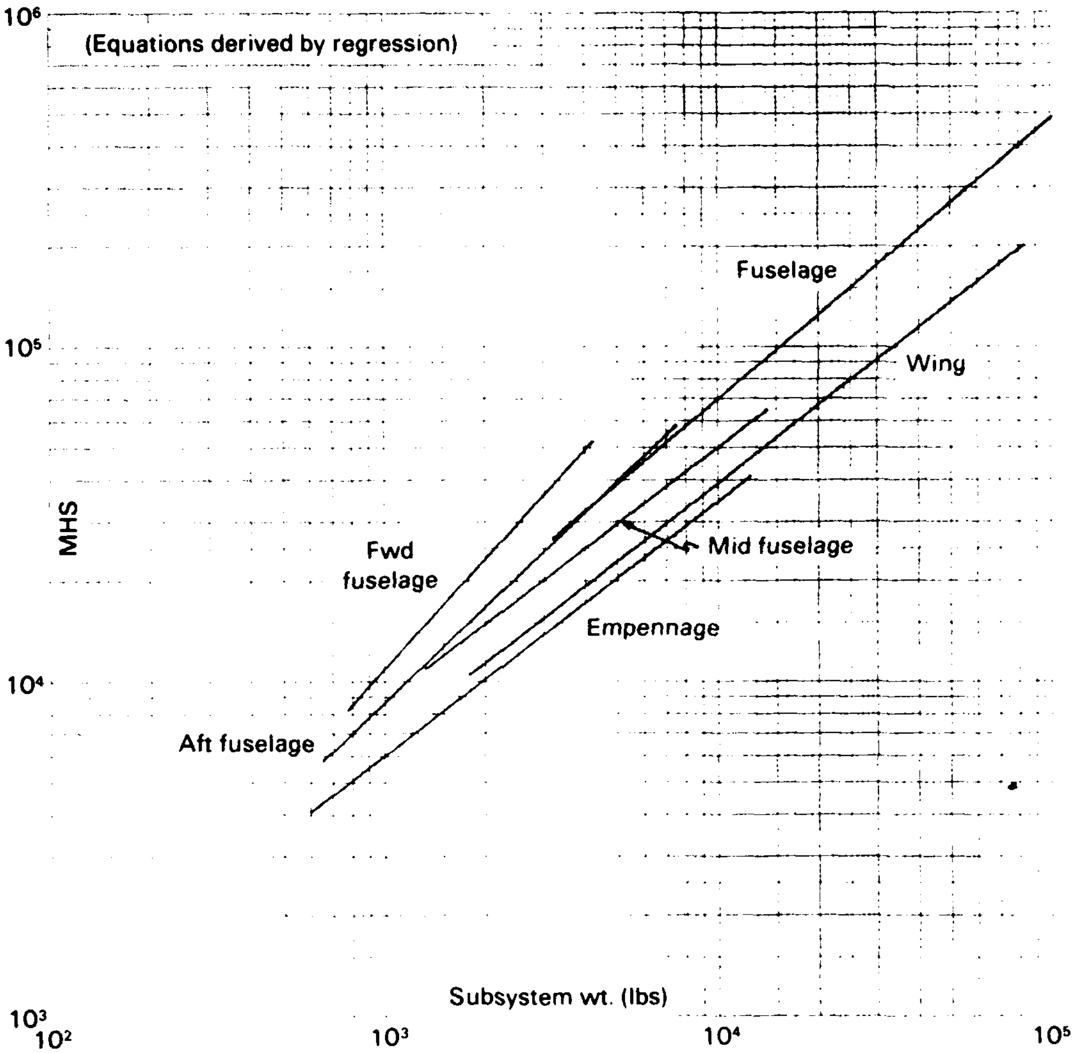

Fig. 8—Production MHS* vs group weight

*100th unit cum ave value

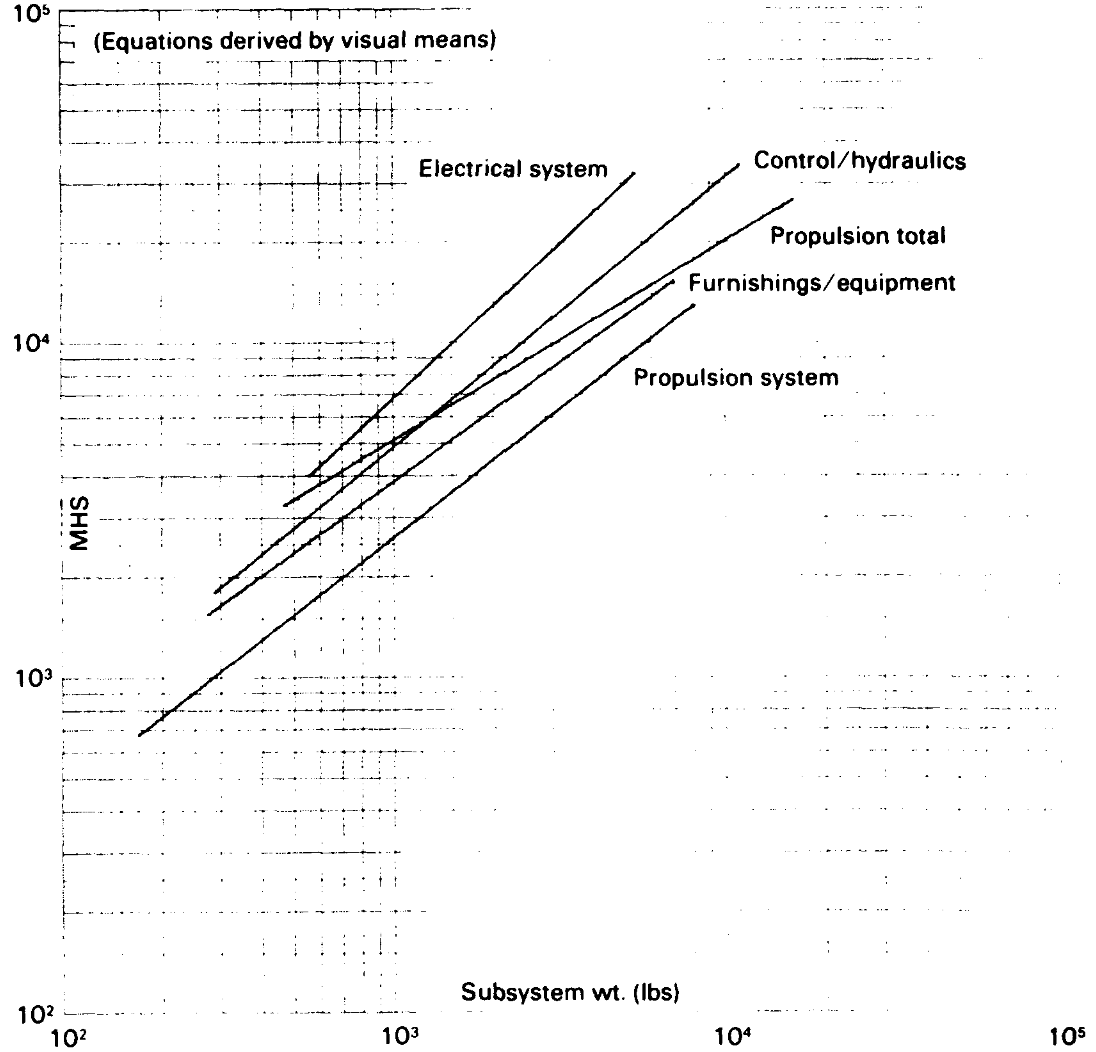

Fig. 9—Production MHS* vs group weight

*100th unit cum ave value

9 show hours-vs-weight plots for groups for which regression and visually derived equations could be obtained. Weight is the only acceptable independent variable, and the ARCO or scaling effort is visible in all equations; that is, increases in size are accompanied by less than proportionate increases in hours.[1]

It is commonly held in the airframe industry that learning curves are flatter in modification programs, because fabricating, assembling, and installing new components in a mod program are not identical to those processes in a production program. A great deal of highly skilled handwork is required where corrosion or manufacturing variances exist. The condition of an airplane influences the amount of work needed; and Boeing-Wichita has found that training-command aircraft and aircraft having a high utilization rate, returning from combat, and based overseas or near sea water will require additional work. Manufacturing hours are also said to be sensitive to aircraft age. Many of the problems that arise from field use and age could manifest themselves in the disassembly process; old rivets may have to be drilled out rather than punched out, creating a need for an oversize rivet. Such problems are thought to reduce the opportunity for labor learning.[2]

Several industry estimators state that learning curves should be up to 10 percent flatter in a mod program, but they were assuming

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[1] This concept dates back to the early 1940s and the so-called ARCO factor (which took its name from the WW-II Aircraft Resources Control Office).

[2] Delays that occur when aircraft are not delivered for modification on schedule are another possible cause of increased labor hours.

production curves steeper than the 77 percent curves shown in Table 16. We must reiterate the need for judgment. For modifications that are primarily structural and for aircraft in good condition the calculated slopes appear to be reasonable.

Up to this point we have been discussing manufacturing as though it were a single process. For reasons pertaining to Air Force budget categories, manufacturing is generally estimated as two separate processes: kit fabrication and installation. The former is in the Aircraft Procurement budget category (3010) and the latter in Operations and Maintenance budget category (3400). Unfortunately, our procedure does not offer a means of estimating these separately. The manufacturing hour data collected contained both fabrication and assembly hours and a portion of the latter would be included in installation. The installation phase would also include disassembly and final reassembly. The equations in Table 16 produce estimates, however, that on the basis of our limited sample of test cases are high enough to include both kits and installation. As indicated by the data below, the two appear to be close enough to 50/50 to make that an acceptable basis for preliminary estimates. The C-5 split is probably inaccurate because assembly hours

KIT/INSTALLATION PERCENTAGES

	ICA	Contractor
B-52	--	37/63
C-5	49/51	55/45
C-141	57/43	46/54
EF-111	38/62	52/48

that would normally be included in kit fabrication (Phase III) have been included in installation (Phase IV) by Air Force direction. Such decisions illustrate the difficulty of separating the two by by after-the-fact analysis.

TEST CASES

B-52 ECP 1581

The total production-hour estimate for 80 aircraft obtained from the Rand equation exceeds the Boeing figure by over 30 percent. Despite the contention that learning curves are flatter in modification programs, the actual slope for this program was very steep. Hours as reported to the Air Force produce a curve with less than a 70 percent slope, for both kits and installation. Boeing explains that this modification consisted mostly of large parts that have low hours per pound and a steep learning curve associated with them.

C-5A Wing Mod

The Rand estimate of total production hours for 76 C-5A wing modifications is about 10 percent higher than the Air Force ICA and 15 percent higher than the Lockheed-Georgia estimate. The Rand Unit 1 estimate, however, is almost 35 percent higher than the ICA. This large difference is attributable to the assumption that learning gained during the original production program will carry over into the modification program; e.g., initial production problems would not be as severe. The

ICA assumes a flatter curve--82 percent--for fabrication and a segmented curve for installation: 80 percent for the first 13 units, then 70 percent for the remainder. The composite slope is 78 percent compared with 76.8 percent from the Rand equations.

C-141 Fuselage Stretch

The Rand equations for mid-fuselage produce an estimate that is between the ICA and Lockheed-Georgia estimates--2 percent lower than the former, 10 percent higher than the latter. On closer inspection, however, the Rand estimate offers little comfort. It differs from known Unit 1 hours for fabrication, assembly, and installation by a wide margin; and as expected, it is on the high side. Only by virtue of a steeper learning curve does the total estimate appear close to the other two estimates.

EF-111A

The ICA estimate is highest of the three available for EF-111A comparisons. The ratios are:

Rand = 1.0
Grumman = 1.27
ICA = 2.02

Differences stem primarily from the choice of learning-curve slope. A 76 percent learning curve, predicted by the Rand method, is considered too steep by Grumman and the ICA team. An 85 percent overall slope was used in the ICA for fabrication and assembly; if used with the Rand equation, they and the ICA estimates would be identical. A possible reason for differences in EF-111A estimates is that Grumman was not the

original manufacturer, although it does have production experience on certain F-111 structural assemblies.

SUMMARY

Our initial hypothesis was that modifications would have a lower Unit 1 value and possibly a flatter learning curve than original production program data. The test cases reveal that the modification process does not lend itself to such simple generalizations (see Table 17). The one case where actual hours are known--the B-52 ECP 1581--had an exceptionally steep learning curve, and actual Unit 1 hours were almost 20 percent higher than the Rand equations predicted. For the C-5A wing mod and the C-141 fuselage stretch, contractor estimates of Unit 1 hours are less than the equations predict and the learning curve slopes are flatter. In the case of the EF-111, only the Rand and Grumman total hour estimates had reasonable agreement. The ICA estimate was substantially greater.

Although the Rand equations are important first steps in estimating modification labor hours, most estimators would agree that values other than the original Unit 1 and learning curve slope can be justified.[3] Whether the values should be increased or decreased depends on such factors as type of part being produced, age of the aircraft, similarity of the production process to the original production program, and employee skill levels.

[3] As a test we substituted different unit costs for the Unit 1 value--the 5th and 25th unit. The reasoning was that the contractor should benefit from prior experience and would not restart at the original Unit 1 value. Unfortunately, the results were no more edifying than those produced by the method described here.

Table 17

COMPARISON OF RAND METHOD WITH ACTUAL PRODUCTION HOURS[a]

Program	P_1 Adjustment Factor		Learning Curve Slope[b]		Total Hours
	Factor Required	Initial Rand Estimate	Observed	Initial Rand Estimate	Deviation Using Rand Method[c]
B-52 ECP 1581	> 1.0	1.0	< 70	77	-.32
C-5A wing mod	.67[d]	1.0	80	77	-.15
C-141 stretch	.51[d]	1.0	83	76	.02
EF-111 mod	.95	1.0	87	76	.51

[a]Where actual data are not available the latest ICA or contractor estimate was used.

[b]Learning curve slopes are composite values.

[c]$\text{Deviation} = \dfrac{\text{Total Observed Hours} - \text{Rand Estimate}}{\text{Total Observed Hours}}$.

[d]Estimates used a different unit cost for the Unit 1 value.

VI. QUALITY CONTROL

Quality control refers to the hours expended to ensure that prescribed specifications and standards are met. It includes such tasks as receiving inspection; in-process and final inspection of tools, parts, subassemblies, and complete assemblies; and reliability testing and failure review.

Quality control is closely related to direct manufacturing labor but has been recorded as a separate account on most aircraft since the mid 1950s. Before that time it was treated as an overhead charge. We were not able to address quality-control directly, because the aircraft group data contained very little such information. In lieu of developing equations, we compared quality-control hours on original programs and their subsequent modification programs.

It is difficult to generalize about quality control hours except to observe that they exhibit different patterns when examined as a percentage of manufacturing labor hours, as is done Table 18. It is clear that estimates have been based on original program percentage when projecting modification quality-control hours. From the B-52 data, where actual hours are available, a reduced percentage may be in order for modification programs. However, we suggest that original program percentages be used for estimating quality-control hours related to aircraft structural modifications until more data become available.

Table 18

CUMULATIVE QUALITY CONTROL HOURS WITH COMPARISON
OF ORIGINAL AND MODIFICATION PROGRAMS

Program	Original Program	Modification Program
B-52	.10	.07
C-5A	.10	.09[a]
C-141	.10	.10[a]
EF-111	.17	.17[a]

[a]Where actual data are not available the latest ICA or contractor estimate is used.

VII. MANUFACTURING MATERIALS

RECURRING MATERIALS COST

Maufacturing materials include raw and semifabricated material plus purchased parts (standard hardware items such as electrical fittings, valves, and hydraulic fixtures) used in the manufacture of airframe assemblies. This category also includes major purchased equipment--such items as actuators, motors, generators, landing gear, instruments, and hydraulic pumps--whether procured by the contractor or furnished by the government. When such equipment is designed specifically for a particular aircraft, it is considered to be subcontracted, not purchased equipment.

Certain items of purchased equipment are furnished to the contractor by the government. Such government-furnished aircraft equipment (GFAE) typically includes wheels, brakes, tires, standard electrical equipment, and flight instruments. GFAE cost is not included in contractor reports and must be sought out in government records for each aircraft program. The cost data used in this report do not include GFAE.

The material cost information provided by the manufacturers required adjustment to ensure a reasonably consistent and comparable data base. Material costs were adjusted for price-level changes over the years to make them comparable. The index numbers used are shown below in Table 19. After all adjustments to the data were made, the percentage of material cost attributed to each aircraft group was calcu-

Table 19

INDEX FOR CONVERSION OF AIRFRAME MATERIALS COST TO CONSTANT 1977 DOLLARS[a]

Year	Index
1958	2.820
1959	2.720
1960	2.608
1961	2.535
1962	2.445
1963	2.491
1964	2.313
1965	2.238
1966	2.150
1967	2.055
1968	1.957
1969	1.825
1970	1.702
1971	1.649
1972	1.573
1973	1.499
1974	1.300
1975	1.171
1976	1.082
1977	1.000

[a]The index was developed by H. Campbell following the procedure described in Aerospace Price Indices, The Rand Corporation, R-568-PR, December 1970.

lated. A comparison of those percentages, provided in Table 20, showed clearly that statistical analysis would be difficult.

The cost-quantity effect can be observed in all aircraft programs examined. However, the variation in slopes is so great that additional data adjustments may be required. An example of such variation is given

Table 20

ALLOCATION OF MATERIAL COST[a]

(Percent spent on Unit 1)

	C-5A	C-130A	C-141A	F-4	F-14A	F-14	F-16
Wing	16.2	28.8	32.8	18.4	5.8	21.0	1.1
Forward fuselage			4.0	7.9	4.5	3.7	3.3
Mid fuselage	31.4	42.4	6.0	28.8	8.0	24.1	3.3
Aft fuselage			10.2	12.3	5.8	25.1	0.6
Empennage	2.6	9.2	6.6	2.4	2.4	10.9	1.5
Landing gear	13.7	1.3	2.8	1.0	3.8	3.1	5.3
Flight controls	4.5	2.1	7.8	5.6	13.7	4.1	9.1
Hydraulic	1.3	1.2	2.5		--		1.8
Propulsion	10.5	2.5	5.2	--	10.2	--	--
Fuel system	--	--	0.6	1.2	--	0.5	1.3
Electrical	3.1	4.1	5.0	17.0	14.1	4.0	5.7
Avionics	17.7	0.6	6.2	--	--	--	45.3
ECS	1.9	1.4	5.1	--	--	--	1.2
Furnishings and equipment	1.0	4.9	3.2	1.4	3.2	2.6	--
Integration	2.5	1.5	3.7	--	0.9	--	--

[a]Percentages do not necessarily total 100 percent.

-- Data not available.

in Table 21 for the wing. Undetermined price-level changes, unusual purchasing patterns, differing accounting procedures, or other causes may contribute to slope disparity. The mean slope shown for the wing in Table 21 is the same as that obtained from samples of total airframe in earlier Rand studies.

Regression analysis was successful in yielding material cost estimating relationships for all but one structural group and for the furnishing category. An equal number of relationships were derived visually for the other categories. Weight was the only explanatory variable found to be statistically significant. Estimating equations for the 100th cumulative average cost together with the related learning curves for each aircraft group are shown in Table 22. Figure 10 con-

Table 21

WING MATERIAL COST-QUANTITY SLOPES

Aircraft Type	Slope (%)[a]
Attack	91
Cargo	87
Cargo	98
Cargo	74
Fighter	88
Fighter	89
Fighter	95
Patrol	72
Mean	86.8

[a] Cost-quantity slopes were either calculated or provided by the manufacturer.

tains plots of cost-vs-weight for the groups for which regression equations could be obtained. Figure 11 displays plots of equations obtained by visual means.

TEST CASES

B-52-ECP-1581

An estimate was made of the total recurring material cost for the B-52 modification program using the parametric equations shown in Table 22. *Our estimate was more than twice as high as the reported cost.* The principal reason for the large discrepancy appears to be that the wing material equations include all materials supplied by contractors for a stuffed wing--one containing wiring harnesses, plumbing, control cables, pumps, actuators and linkages--the B-52 modification involved mostly structure and consequently very little purchased equipment was needed. If the percentage that purchased equipment contributed to the original total airframe material cost is used to adjust the initial estimate downward to account for the absence of purchased equipment, reasonable agreement with reported cost can be achieved.

C-5A Wing Modification

The unadjusted parametric equations produce a much higher cost than projected by either the ICA or Lockheed for the C-5A wing mod. As in the case of the B-52 ECP-1581, this modification involves mainly structure; most of the purchased equipment in the areas affected will be removed, checked, and reinstalled. Purchased equipment made up about 40

Table 22

MATERIAL COST ESTIMATING RELATIONSHIPS

(100th unit cumulative average cost)[a]

Group	Estimating Relationship	Type of Derivation	Observation	Statistics R^2	Statistics Mean	Statistics SEE	Cost-Quantity Factor b	Cost-Quantity Factor L(%)	Range of Independent Variable (lb)
Wing	$M_{100} = 27.71\ W^{1.03}$	Regression	7	.91	12.58	.49	-.25	84	1,800 - 82,000
Fuselage	$M_{100} = 120.5\ W^{.89}$	Regression	8	.86	13.01	.45	-.22	86	3,500 - 116,000
Forward fuselage	See plot in App. B	--	6	--	--	--	-.20	87	750 - 2,746
Mid fuselage	$M_{100} = 3500.7\ W^{.43}$	Regression	6	.55	11.67	.41	-.25	84	1,300 - 19,000
Aft fuselage	$M_{100} = 234.88\ W^{.81}$	Regression	6	.79	11.39	.46	-.26	84	600 - 7,600
Empennage	$M_{100} = 517.17\ W^{.70}$	Regression	7	.95	11.60	.19	-.17	89	620 - 12,600
Landing gear	$M_{100} = 48.3\ W^{.95}$	Visual	8	--	--	--	-.25	84	650 - 28,000
Electrical	$M_{100} = 858\ W^{.66}$	Visual	7	--	--	--	-.23	85	550 - 5,300
Controls/hydraulics	$M_{100} = 97.9\ W^{.94}$	Visual	6	--	--	--	-.25	84	1,100 - 11,100
Furnishings/equipment	$M_{100} = 37.64\ W^{.92}$	Regression	7	.85	10.19	.50	-.40	76	280 - 6,900
Environmental controls	See plot in App. B	--	5	--	--	--	-.25	84	180 - 3,700
Propulsion-total	$M_{100} = 319.2\ W^{.73}$	Visual	6	--	--	--	-.06	96	450 - 16,500
Fuel system	See plot in App. B	--	4	--	--	--	-.09	94	300 - 1,300
Propulsion system	$M_{100} = 644.2\ W^{.60}$	Visual	4	--	--	--	-.14	91	150 - 8,000
Avionics	See plot in App. B	--	4	--	--	--	-.16	90	30 - 1,700
System integration	$M_{100} = 31.5\ W^{.68}$	Visual	5	--	--	--	-.23	85	9,000 - 283,000

[a]In 1977 dollars.

-- Not applicable.

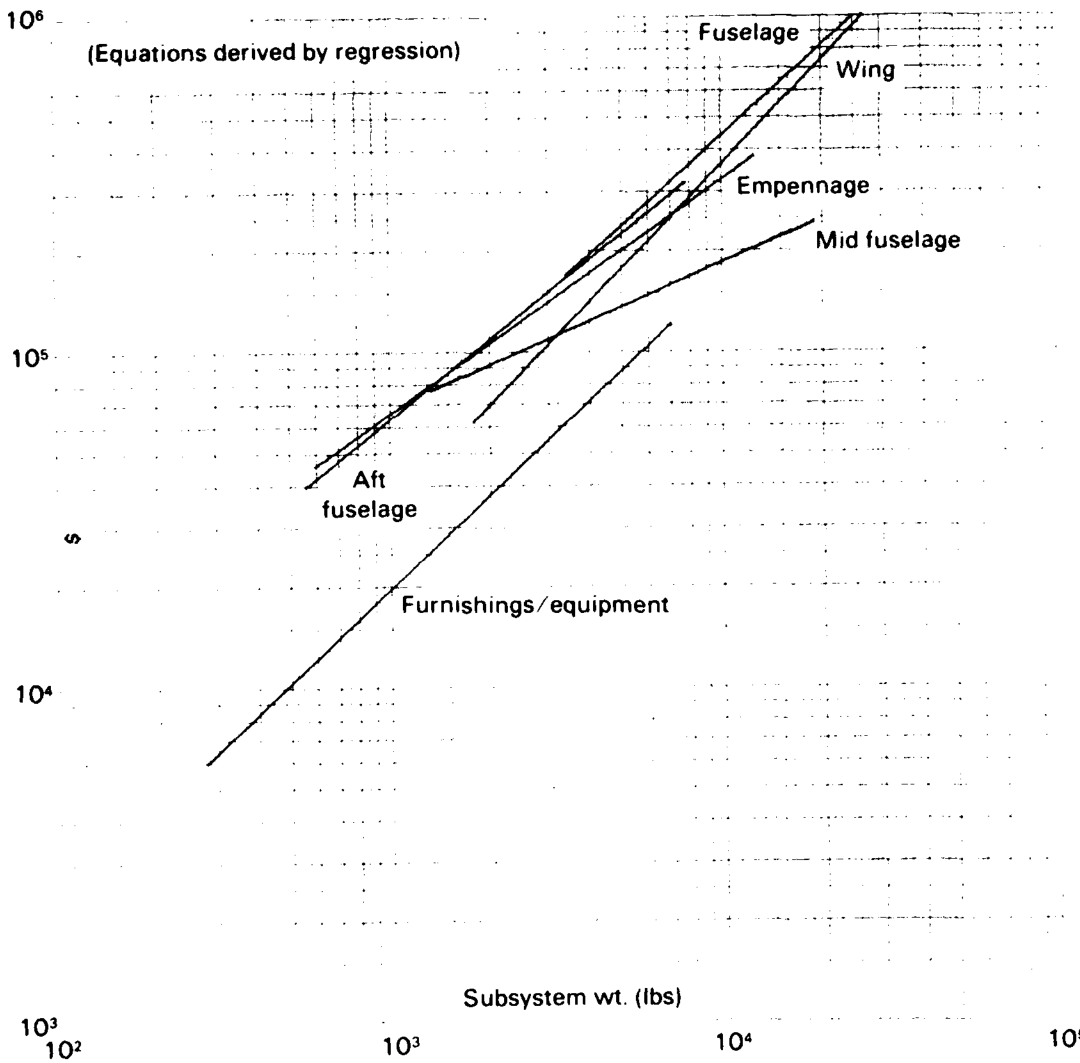

Fig. 10—Material $* vs group weight

*100th unit cum ave value

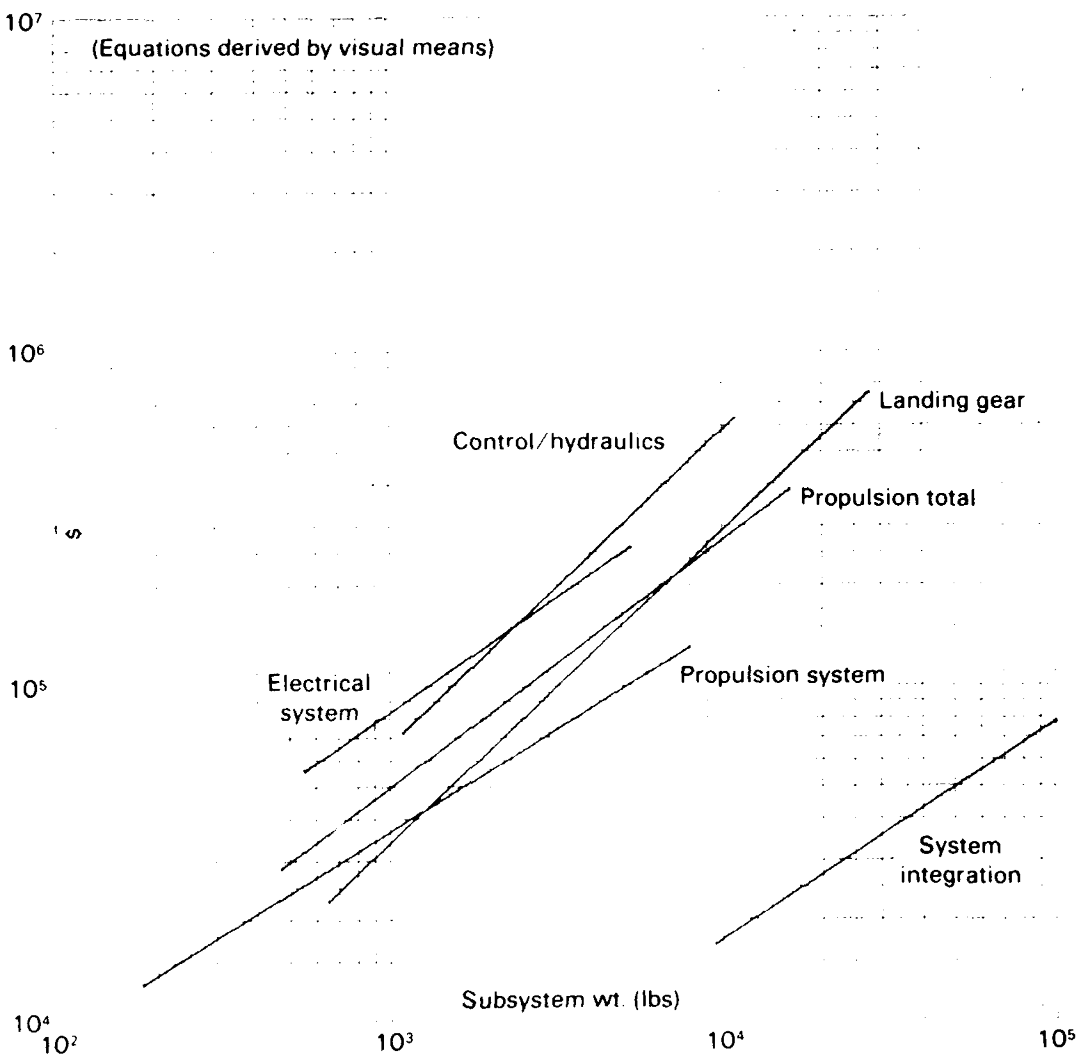

Fig. 11—Material \$* vs group weight

*100th unit cum ave value

percent of the original wing material costs. If the value for total material predicted by the parametric equations is adjusted downward by 40 percent, the result is a material cost estimate that is within 28 percent of the cost currently being projected. The format of the modifications material cost values did not allow determination of either a Unit 1 or learning curve slope.

C-141 Fuselage Stretch

Consistent with the previous two test cases, the parametric equations provide an unadjusted estimate that is considerably higher than the current material cost projection. Similarly, little new purchased equipment is required. If a 40 percent downward adjustment (to account for the absence of purchased equipment) is applied, the total Rand estimate exceeds the currently projected material cost by 33 percent.

EF-111A Conversion

For this modification, the parametric relationships predict slightly more than half of the total material cost value estimated in the ICA. This difference appears to stem from the flatter slope (98 percent) used in the ICA than Rand's estimate of 89 [illegible]. The 98 percent curve used in the ICA is said to reflect the small quantity involved (42 aircraft) and the resulting problems encountered by the contractors in obtaining aluminum from the suppliers with normal volume discounts. If a 98 percent curve is applied to the Rand M_1 estimate, total material cost is within a few percentage points of the projected cost.

SUMMARY

For the test cases, the observed M_1 value and corresponding slopes could not be determined, with the exception of the EF-111. Accordingly, Table 23 shows only the unadjusted Rand M_1 factor, and the deviations between Rand estimated material cost and observed (or estimated) totals.

Modifications may entail reuse of substantial amounts of original equipment, which for three of the test cases required a downward adjustment in estimates of 40 to 50 percent. Such percentages can be derived from the contribution that purchased equipment made to the original program total material cost. Unfortunately, such percentages could be accurately identified for only a few of the programs in the data base.

Table 23

COMPARISON OF RAND METHOD WITH ACTUAL MATERIAL COSTS[a]

Program	M_1 Adjustment Factor		Learning Curve Slope[b]		Total Hours
	Factor Required	Initial Rand Estimate	Observed	Initial Rand Estimate	Deviation Using Rand Method[c]
B-52 ECP 1851	--	1.00	--	84	-1.38
C-5A wing mod	--	1.00	--	84	-1.14
C-141 stretch	--	1.00	--	84	-1.38
EF-111 mod	1.06	1.00	98	85	.53

[a]Where actual data are not available the latest ICA or contractor estimate was used. Estimate used 1977 constant year dollars.

[b]Learning curve slopes are composite values.

[c]$\text{Deviation} = \frac{\text{Total Observed Costs} - \text{Rand Cost Estimate}}{\text{Total Observed Costs}}$.

-- Values not available.

VIII. CONCLUSIONS

Long-range planning involves consideration of numerous alternatives for achieving specified goals, and for aircraft systems one set of alternatives usually compares acquisition of a new aircraft with modification of one already in the inventory. Planners have found that parametric models involving few inputs provide estimates of cost that are sufficiently accurate for preliminary tradeoff studies. The premise of the present study was that it might be possible to develop a comparable model for estimating modification costs. We recognized from the outset that a simple model would not achieve the objective; however, an over-complicated model would require inputs not easily available. The question was whether a general model could be developed that would be useful for major modifications and still not demand more specialized knowledge than would be readily available to Air Force planners.

Although generous with their time and cooperative in providing data, aircraft industry sources have consistently maintained that detailed knowledge of the original production program and the proposed modification is essential in estimating costs. The preceding sections support that position. An estimator must gauge the technical difficulty of a mod relative to initial development. He must know what tools are needed and which have been stored from the production program. He must know the slope of the fabrication and assembly curve in the original program to decide whether the modification curves will be steeper or flatter than average. The same problem pertains in material costs where use of an industry-wide curve can result in substantial errors. Conse-

quently, a simple, deterministic model would not provide useful estimates of modification costs even in preliminary planning studies.

The need to estimate modification costs at a time when little detailed information is available still exists, however, The question is whether the equations presented offer any assistance to an estimator. We believe that they do when used with discretion and understanding, but some knowledge of an aircraft's production history is essential. Ideally, an agency responsible for estimating mod costs would have such information stored so that it could be referred to when needed. With, say, a notebook on the B-52, C-141, C-5A, etc. that contains both data and a narrative history of the aircraft an estimator would have a basis for making judgments about the modification engineering required relative to initial engineering, the amount of new tooling needed, learning curve slopes, etc.

Also, the equations in this report may have uses for estimating costs in areas other than modifications. Although we have not explored such uses, the equations may have application in design tradeoffs or in coproduction programs where estimates of a wing, empennage, or some other group are needed. For structural components of an airframe the statistical parameters of the equations are generally good and estimates appear reasonable.

Estimating modification costs is a special problem. The equations estimate baseline costs of aircraft components in a conventional development/production program. The extent to which a proposed modification program differs from the original program must be carefully gauged to achieve estimates of acceptable accuracy.

Appendix A

AN ILLUSTRATION

To illustrate the use of the estimating equations presented in this study, consider a hypothetical wing modification program that also involves changes to the electrical system. A total of 150 aircraft are to be modified; the new weight by cost group is shown below:

Cost Group	New Weight (lb)
Wing	10,000
Electrical	2,000
TOTAL	12,000

The procedure to be used is based on the following steps: (1) calculate the 100th cumulative average value using the appropriate equations, (2) obtain a unit-one value using the associated b power, (3) apply adjustment factor if deemed applicable, (4) calculate the average for 150 airframes, and (5) multiply by 150 to obtain total hours (or costs).

Unit 1 is calculated as follows:

$$Y_{100} = Y_1(100)^b$$

$$Y_1 = [Y_{100}]/[(100)^b]$$

Once the Unit 1 value is obtained, the cumulative average hours (or costs) for any quanity can be calculated.

$$Y_{150} = Y_1(150)^b$$

Note that Y_1 is a construct. Its value will change as different cost-quantity curve slopes are derived. Total hours (or cost) are calculated as follows:

$$\text{Total hours (or cost)} = 150\ Y_{150}$$

<u>ENGINEERING HOURS</u> (Reference Table 5)

<u>Wing</u>

$$E_{100} = 84.89W^{.50}$$

$$= (84.89)(10{,}000)^{.50}$$

$$E_{100} = 8489$$

$$8489 = E_1(100)^{-.85}$$

$$E_1 = 425{,}458. \qquad \text{(Unit one value)}$$

Assume that the modification is similar to the C-5A wing mod; the E_1 adjustment factor would be = .5.

$$E_1' = E\ .5$$

$$= (425{,}458)(.5)$$

$$= 212{,}729 \qquad \text{(Adjusted unit one value)}$$

$$E_{150} = (212{,}729)(150)^{-.85}$$

$$= 3007$$

(One could choose a different b value based on experience or other data.)

Wing total engineering hours = (150)(3007)

= 451,050 hr

Electrical (Reference Table 5)

$$E_{100} = 21.4W^{.71}$$

$$= (21.4)(2000)^{.71}$$

$$E_{100} = 4722$$

$$4722 = E_1 \; (100)^{-.79}$$

$$E_1 = 179,525$$

$$\overline{E}_1' = .5(179,525)$$

$$E_1' = 89,763$$

$$E_{150} = 89,763(150)^{-.79}$$

$$E_{150} = 1714$$

Electrical total engineering hours = (150)(1714)

= 257,100

	Engineering Hour Summary		
	Nonrecurring	Recurring	Total
Engineering hours	302,492	405,658	708,150

TOOLING HOURS (Reference Table 13)

Wing

$$T_{100} = 48.62W^{.70}$$

$$= (48.62)\ (10{,}000)^{.70}$$

$$= 30{,}677$$

$$30{,}677 = T_1(100)^{-.83}$$

$$T_1 = 1{,}402{,}209$$

Assume that all the original tooling is available. An adjustment factor identical to that on the C-5A wing mod program can be used--50 percent.

$$T_1(\text{new}) = .5(1{,}402{,}209)$$

$$= 701{,}105$$

$$T_{150}(\text{new}) = 701{,}105(150)^{-.83}$$

$$\text{Wing total new tooling hr} = 150(10{,}955)$$

$$= 1{,}643{,}250$$

$$T\ (\text{inherited}) = .5(1{,}402.209)$$

Assume *300 aircraft were orginally produced.*

$$T_{150}(\text{inherited}) = 701{,}105(450)^{-.83}(450) - 701{,}105(300)^{-.83}(300)$$

$$= 1{,}980{,}749 - 1{,}848{,}816$$

$$T_{150}(\text{inherited}) = 131{,}933$$

$$\text{Wing total inherited tooling hours} = 131{,}933$$

$$\text{Wing total tooling hours} = 1{,}775{,}183$$

<u>Electrical</u> (Fig. B-30, App. B)

$$T_{100} = 1350$$

$$1350 = T_1(100)^{-.81}$$

$$T_1(new) = 56,277$$

$$T_1(new) = (.50)(56,277)$$

$$= 28,139$$

$$T_{150}(new) = (28,139)(150)^{-.81}$$

$$= 486$$

Electrical total new tooling hours = (150)(486)

= 72,900

$$T_1(inherited) = .5(56,277)$$

$$= 28,139$$

$$T_{150}(inherited) = 28,139(450)^{-.81}(450) - 28,139(300)^{-.81}(300)$$

$$= 89,830 \qquad - 83,169$$

$$= 6,661$$

Electrical total inherited tooling hr = 6,661

Electrical total tooling hours = 79,561

Tooling Hour Summary

	Nonrecurring	Recurring	Total
Tooling hours	729,244	1,125,500	1,854,744

PRODUCTION HOURS (Reference Table 16)

Wing

$$P_{100} = 32.1W^{.77}$$

$$= (32.1)(10,000)^{.77}$$

$$= 38,593$$

$$38,593 = P_1(100)^{-.38}$$

$$P_1 = 222,080$$

$$P_{150} = (222,080)(150)^{-.38}$$

$$P_{150} = 33,082$$

Total wing production hours = (150)(33,082)

= 4,962,300

Electrical

$$P_{100} = 26.9W^{.68}$$

$$= (26.9)(2,000)^{.68}$$

$$= 4726$$

$$4726 = P_1(100)^{-.39}$$

$$P_1 = 28,477$$

$$P_{150} = (28,477)(150)^{-.39}$$

$$= 4,035$$

Total electrical production hours = (150)(4,035)

= 605,250

Total production hours = 5,567,550

<u>QUALITY CONTROL</u>

150 modified airframes

QC hours = .10(Production hours) (See Sec. VI.)

= .10(5,567,550)

= 556,755

<u>MATERIAL COST</u> ($77) (Reference Table 22)

<u>Wing Material</u> $

$$M_{100} = 27.71W^{1.03}$$

$$= (27.71)(10,000)^{1.03}$$

$$= \$365,289$$

$$\$365,289 = M_1 \ (100)^{-.25}$$

$$M_1 = \$1,155,145$$

$$M_1' = (.7)(\$1,155,145)$$ (30% downward adjustment: assumes very little new purchased equipment)

$$M_1' - 808,602$$

$$M_{150} = \$808,602(150)^{-.25}$$

$$= \$231,053$$

Total wing material costs = (150)($231,053)

= $34,657,950

Electrical Material $

$$M_{100} = 858W^{.66}$$

$$= (858)(2000)^{.66}$$

$$= \$129,469$$

$$\$129,469 = M_1(100)^{-.23}$$

$$M_1 = \$373,393$$

$$M_1' = (.7)(\$373,393)$$

$$= \$261,375$$

$$M_{150} = \$261,375(150)^{-.23}$$

$$= \$82,558$$

Total electrical material costs = (150)($82,558)

= $12,383,700

Total material costs = $47,041,650

Table A.1

PROGRAM SUMMARY

Cost Element	Nonrecurring	Recurring	Total
Engineering hours	302,492	405,658	708,150
Tooling hours	729,244	1,125,500	1,854,744
Production hours	--	5,567,550	5,567,550
Quality Control hours	--	556,755	556,755
Total Hours	1,031,736	7,655,463	8,687,199
Material Costs[a]	--	$47,041,650	$47,041,650

[a]1977 dollars

Appendix B

DATA PLOTS

This appendix contains the individual plots reported in the body of the report. The plots are organized by aircraft group. Within each group are four plots: engineering, tooling, production, and materials. The solid lines are estimating relationships established by regression analysis; dashed lines are estimating relationships derived by visually fitting a trend line to the data. Several plots were not able to support any type of trend line and are marked with a shaded area to show the region of historical experience.

A derived equation is shown in the upper left hand corner of the plot. All plots have a manhour or cost-quantity factor, b, also in the upper left hand corner. This b value was derived from the mean of manhours or dollars at the 1st, 50th, and 100th unit and can be used to estimate the cumulative average for any quantity using the following relationship:

$$y = a_1 x^b$$

where

y = the hours or cost
a_1 = the cost of the first unit
x = the quantity
b = the cost-quantity factor.

To obtain the a_1 value, substitute for the Y_{100} value the output from a particular equation and solve for a_1.

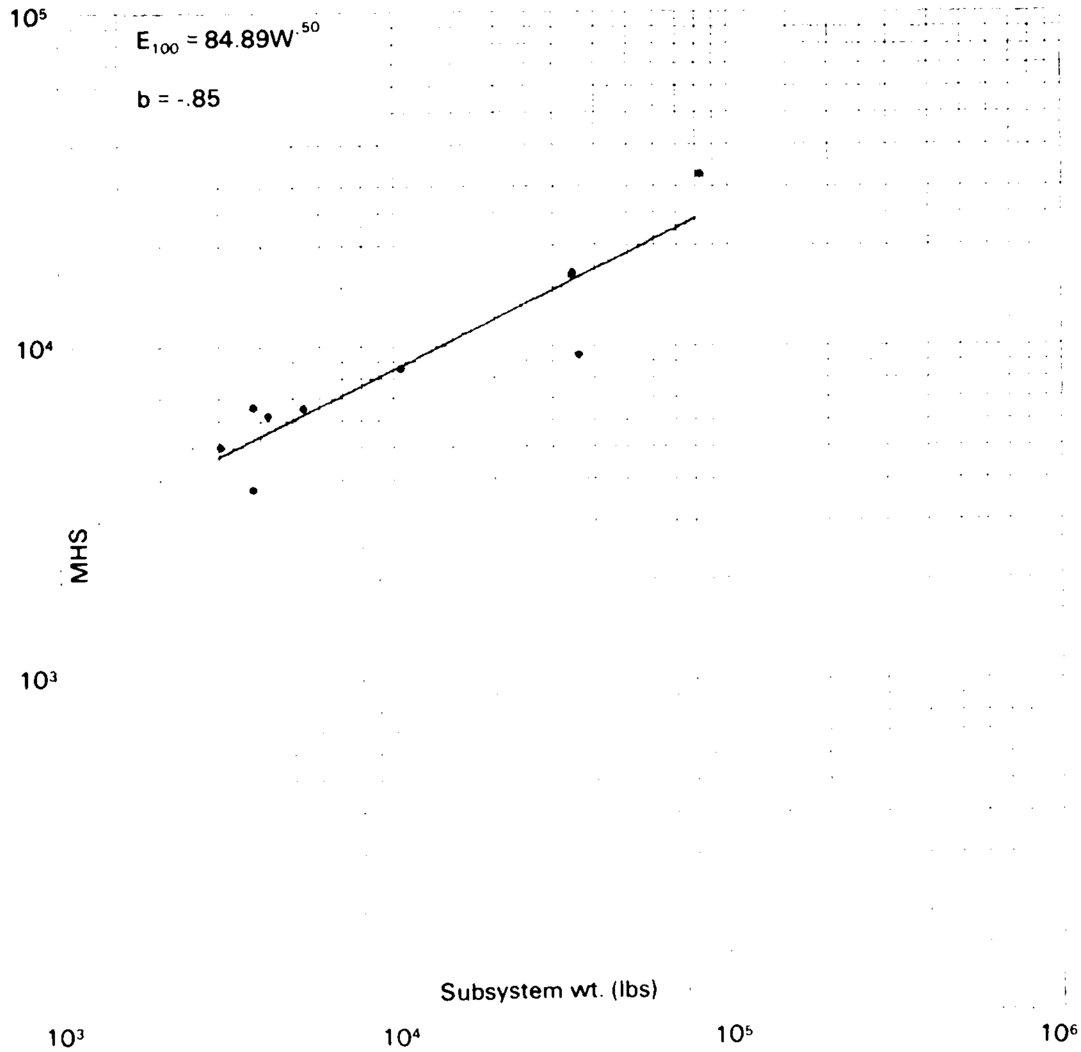

Fig. B-1—Engineering MHS* vs wing weight

*100th unit cum ave value

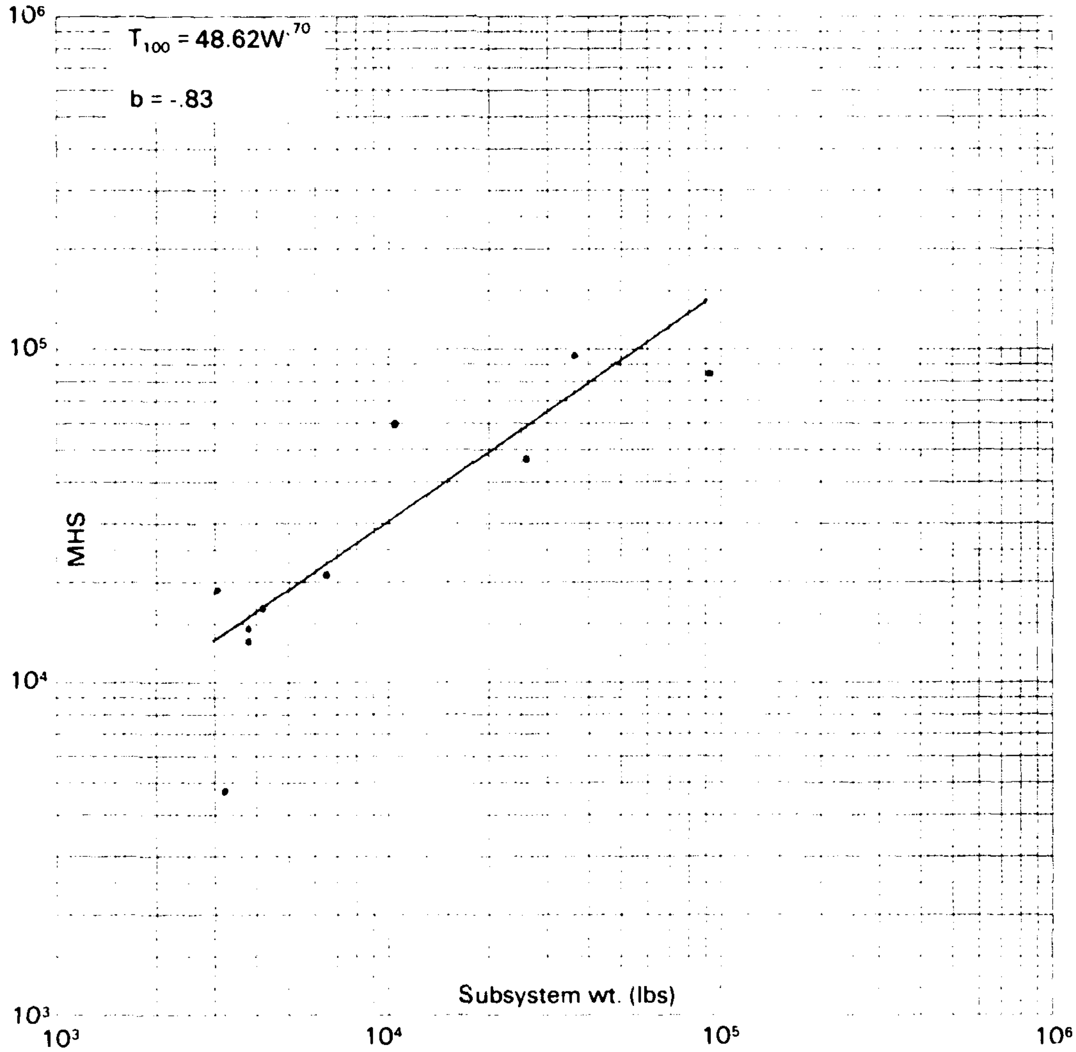

Fig. B-2—Tooling MHS* vs wing weight

*100th unit cum ave value

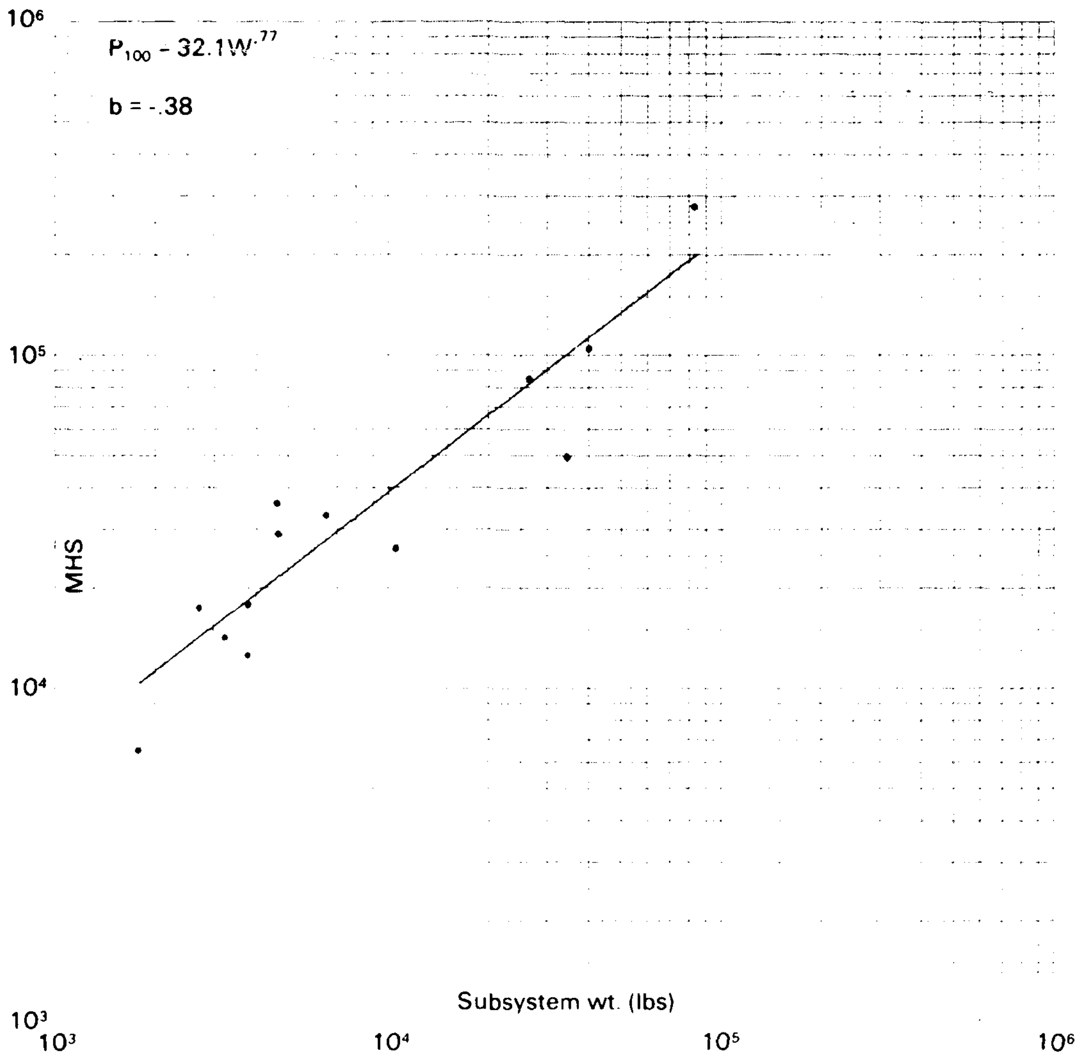

Fig. B-3—Production MHS* vs wing weight

*100th unit cum ave value

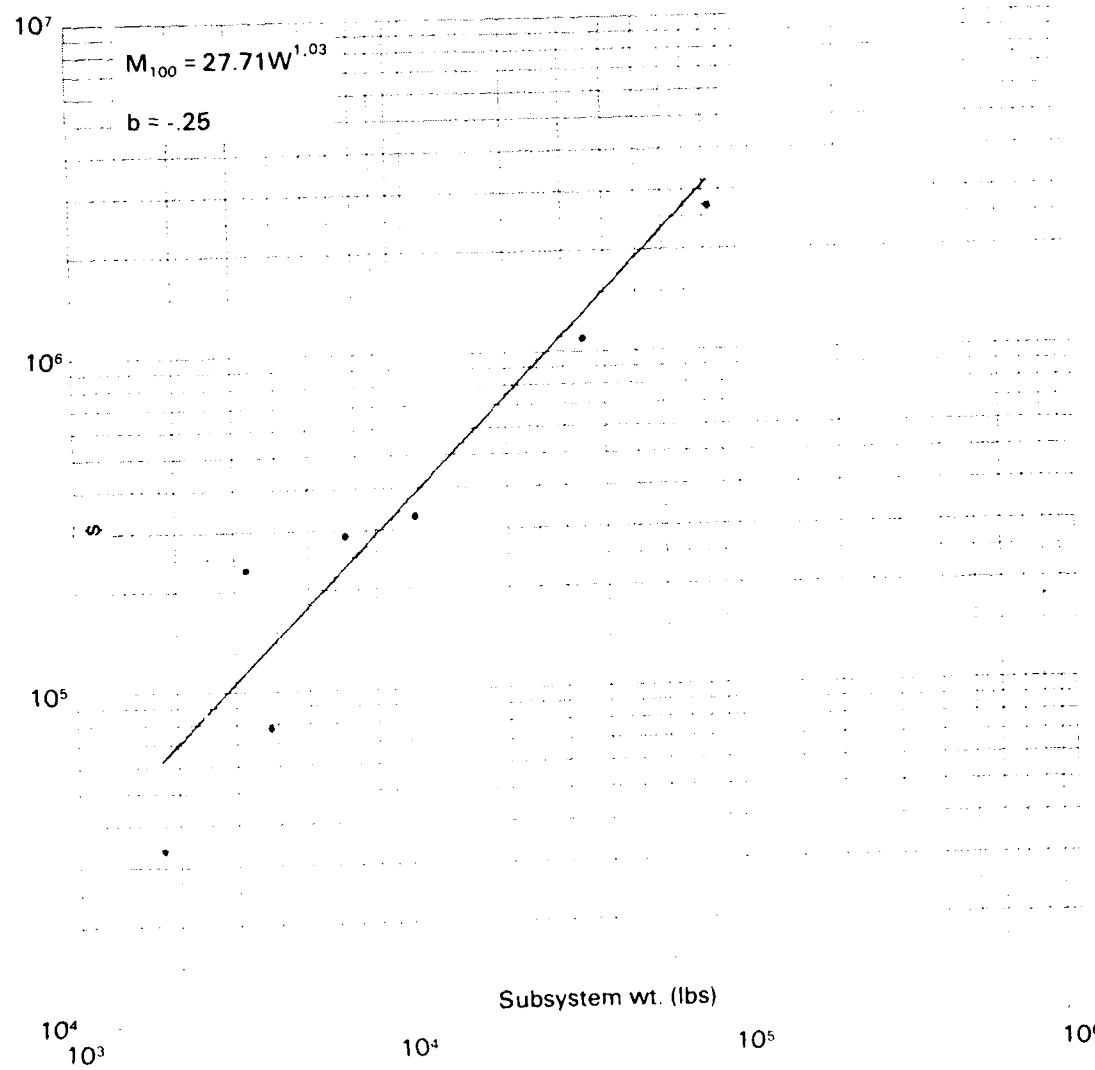

Fig. B-4—Material $* vs wing weight

*100th unit cum ave value

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A METHOD FOR ESTIMATING THE COST OF AIRCRAFT STRUCTURAL MODIFIC--ETC(U)
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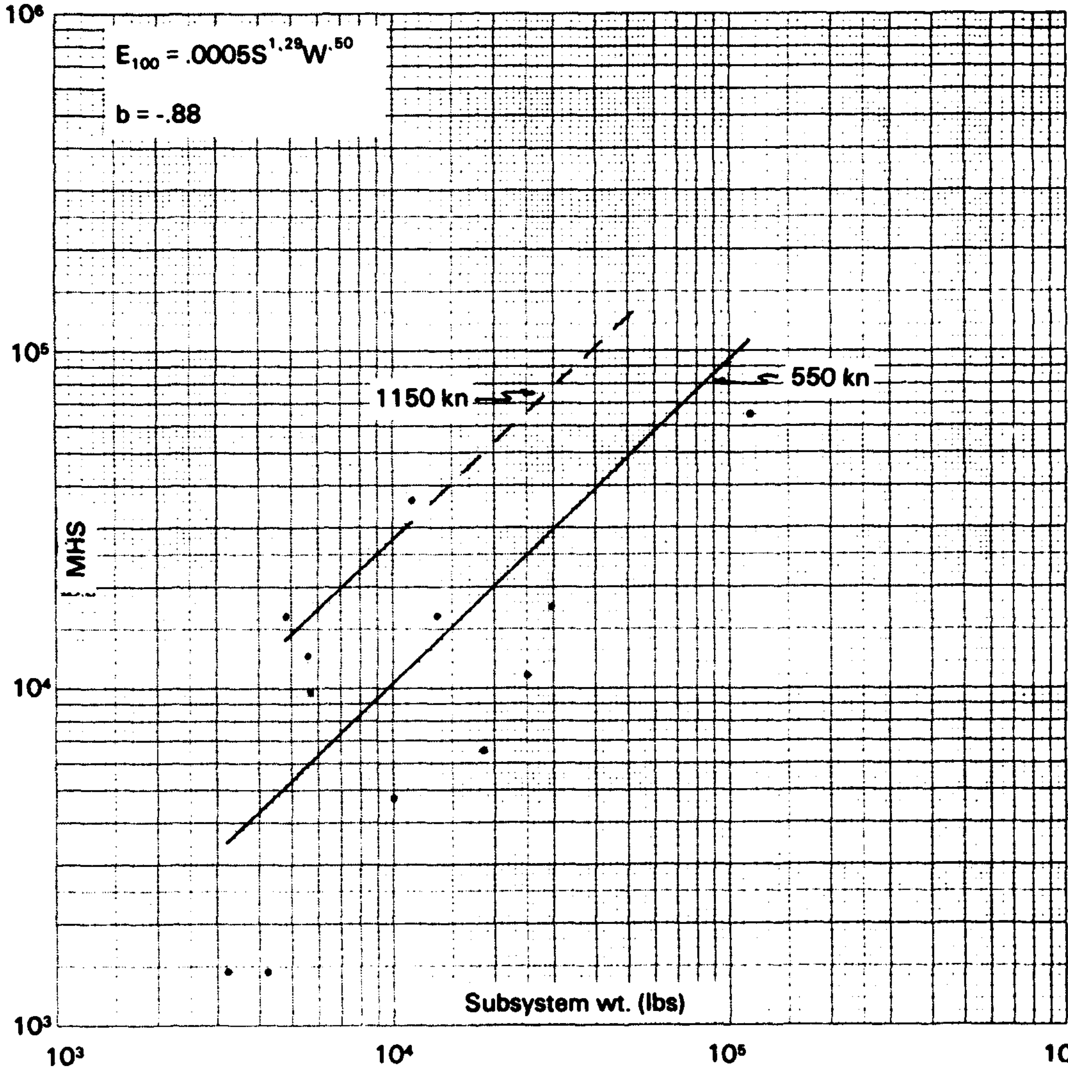


Fig. B-5—Engineering MHS* vs fuselage weight

*100th unit cum ave value

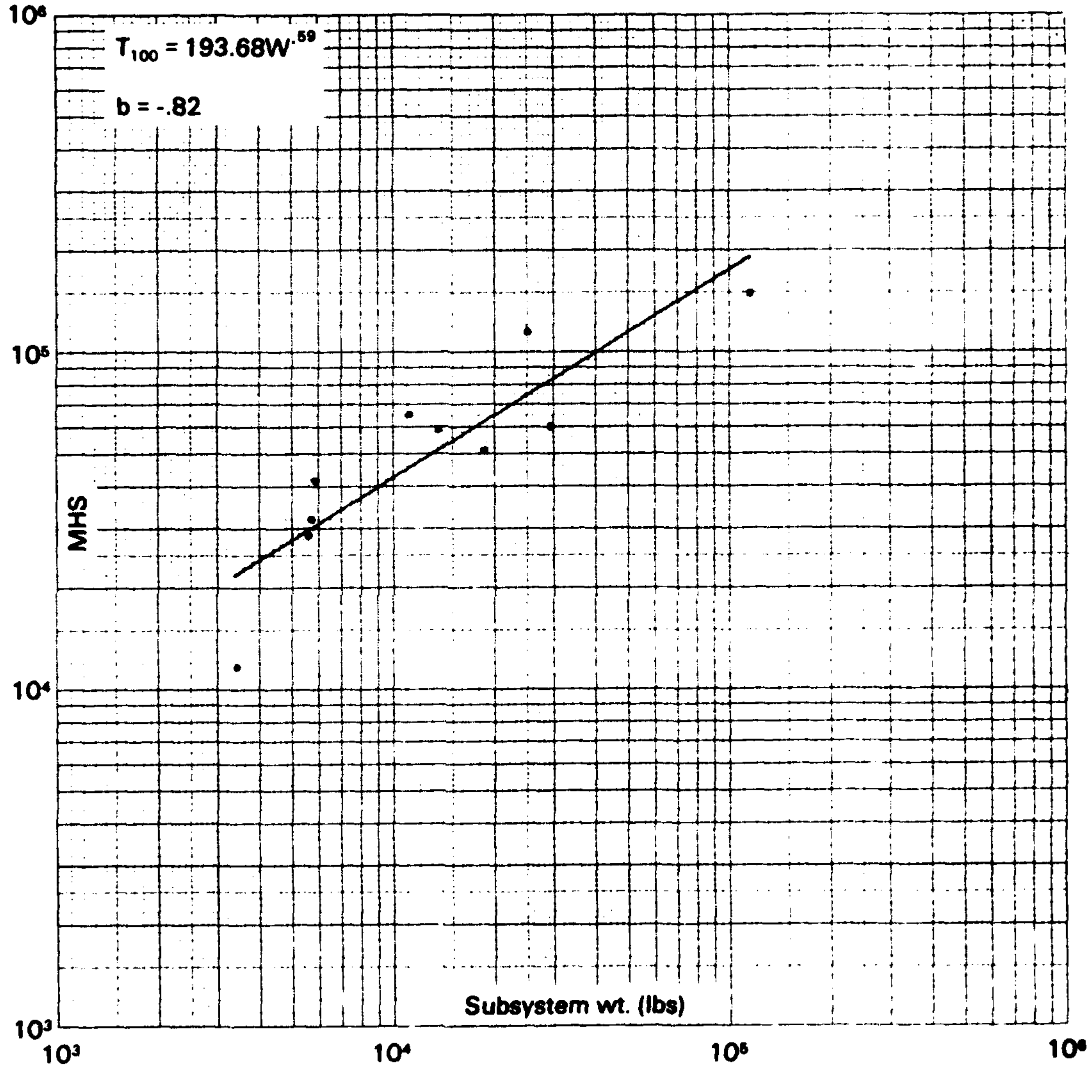


Fig. B-6—Tooling MHS* vs fuselage weight

*100th unit cum ave value

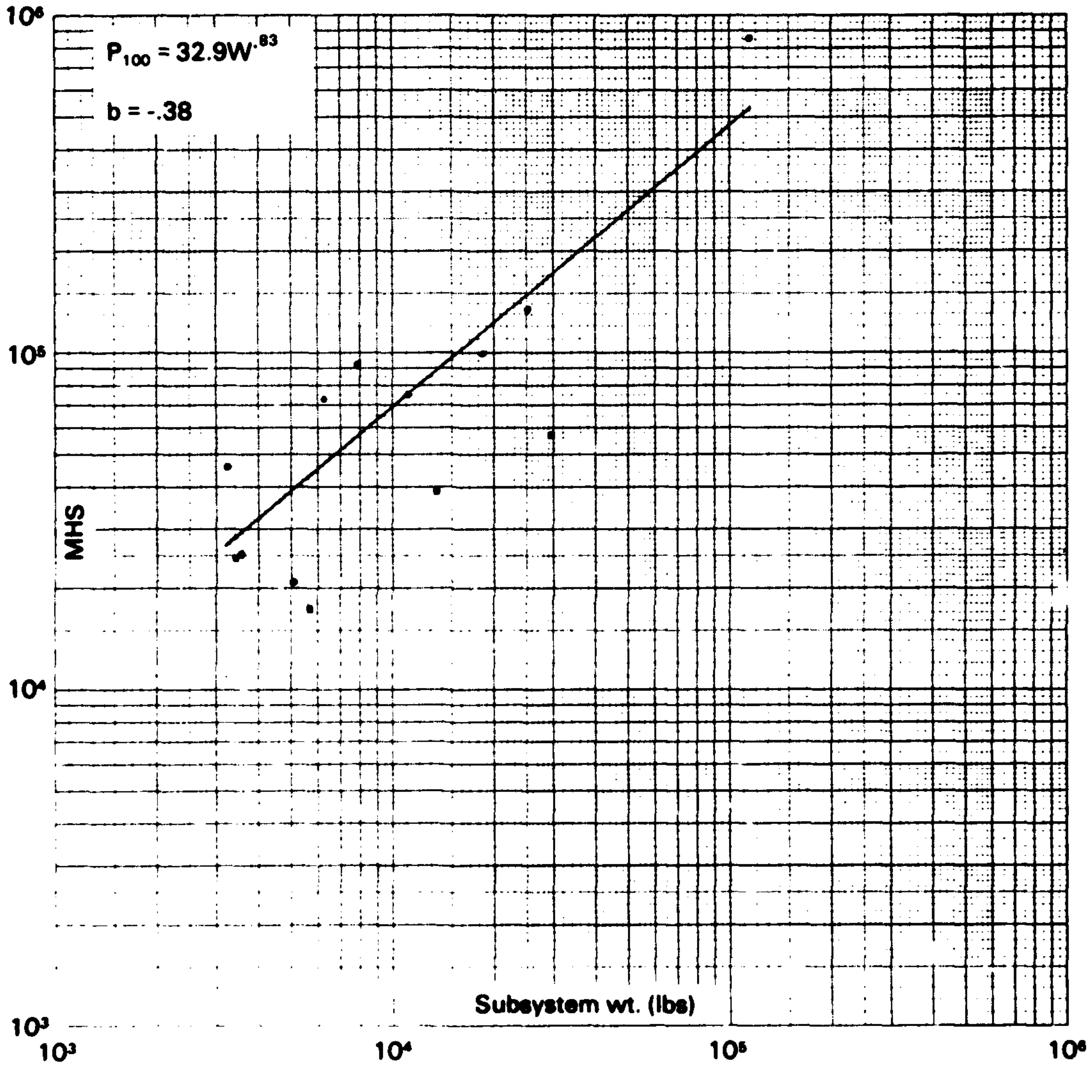


Fig. B-7—Production MHS* vs fuselage weight

*100th unit cum ave value

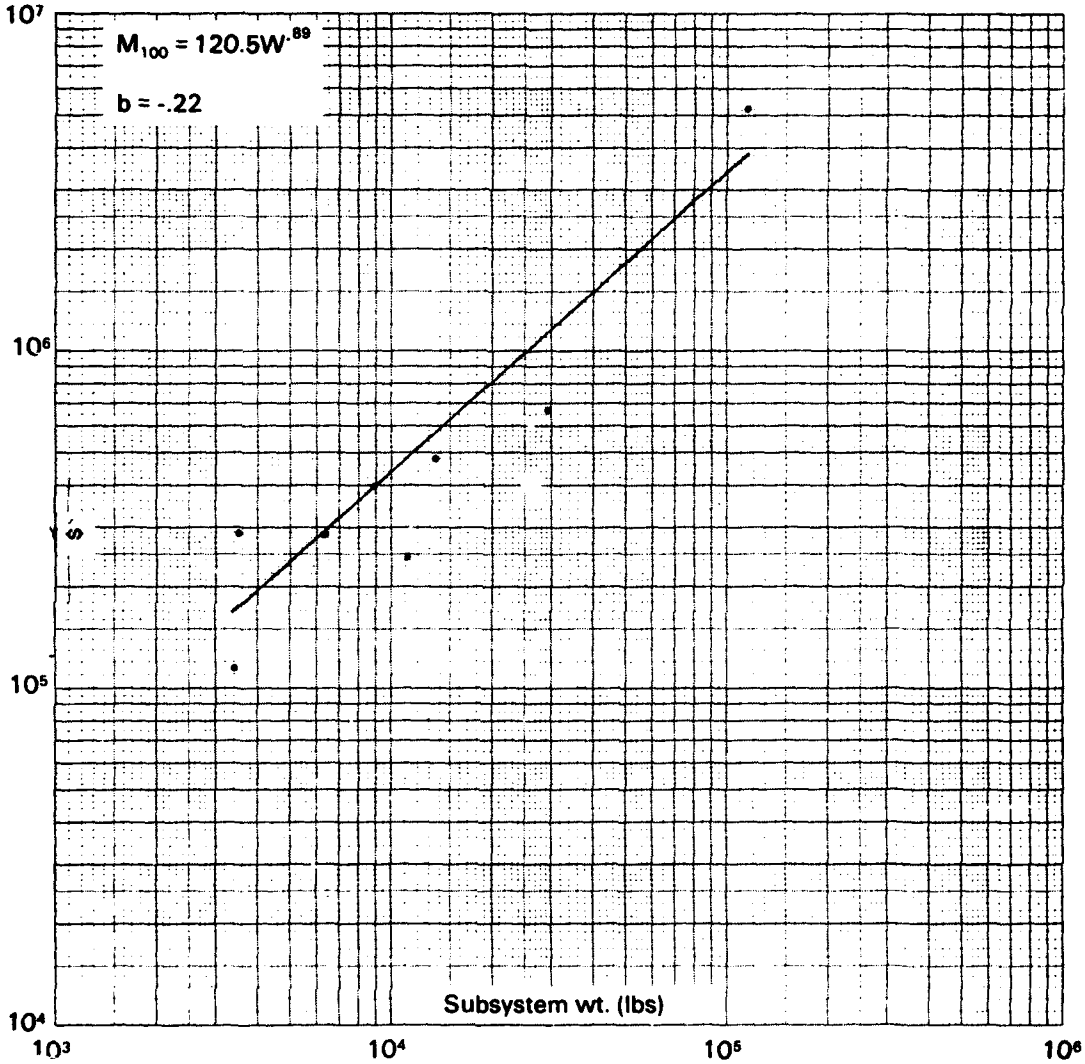


Fig. B-8—Material \$* vs fuselage weight

*100th unit cum ave value

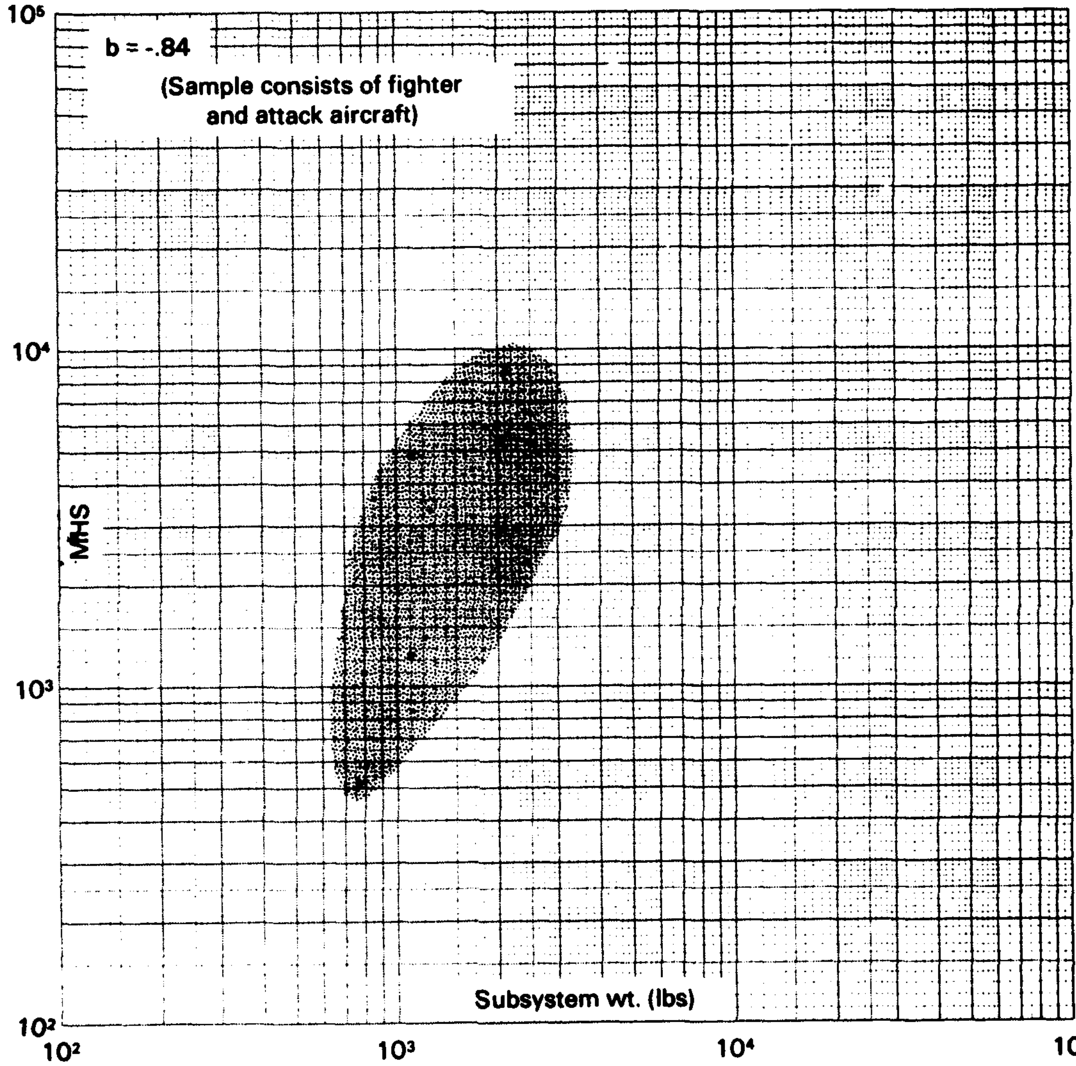


Fig. B-9—Engineering MHS* vs fwd fuselage weight

*100th unit cum ave value

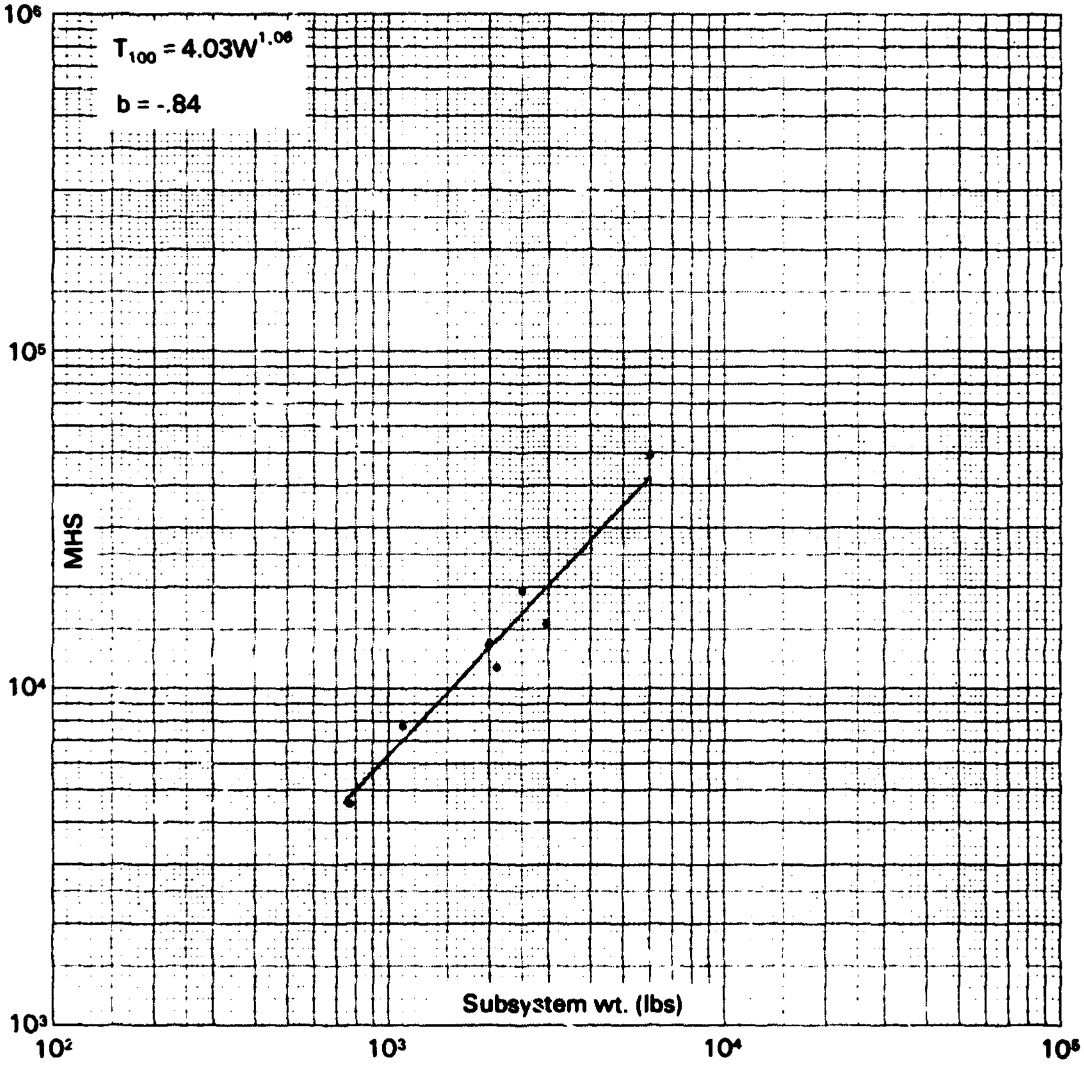


Fig. B-10—Tooling MHS* vs fwd fuselage weight

*100th unit cum ave value

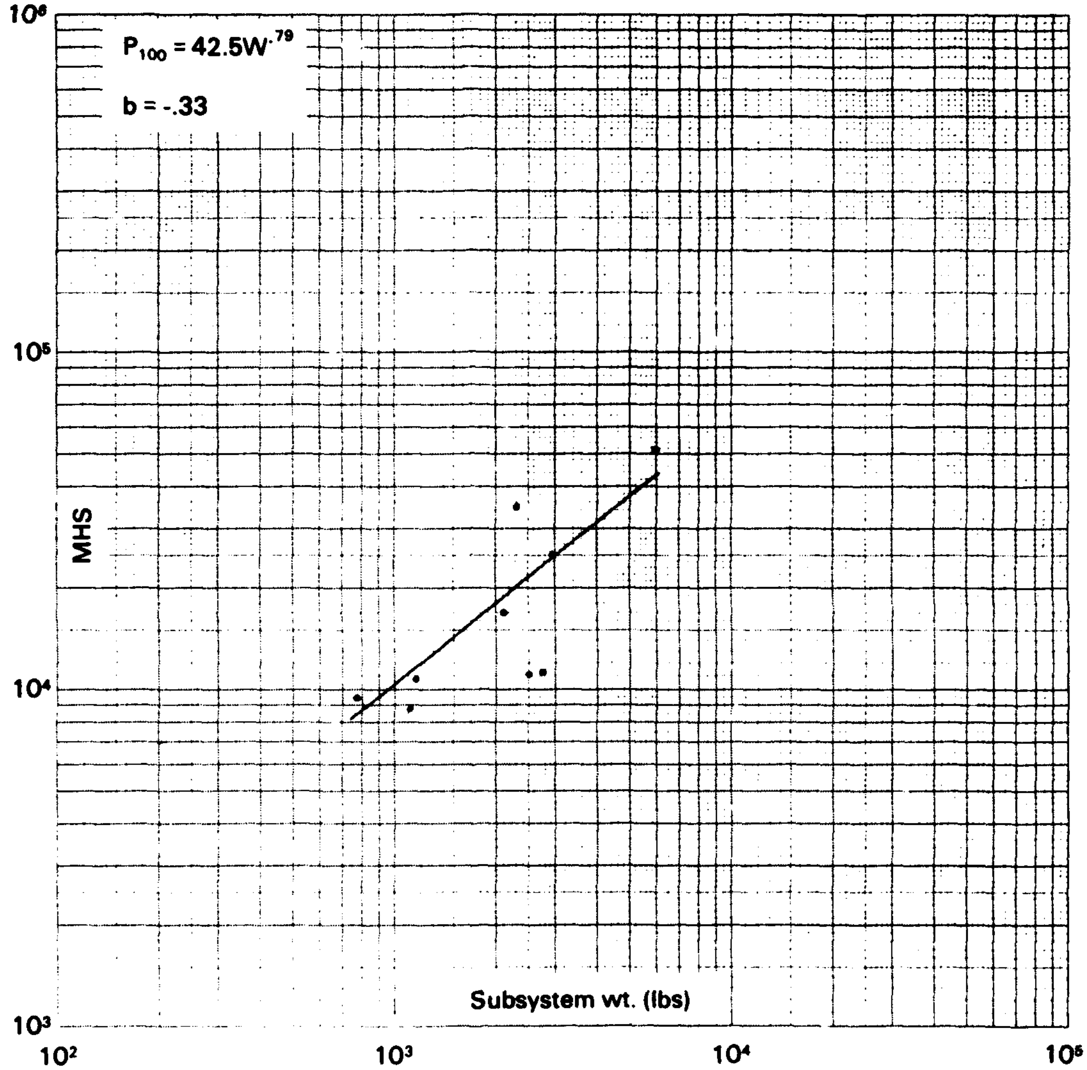


Fig. B-11—Production MHS* vs fwd fuselage weight

*100th unit cum ave value

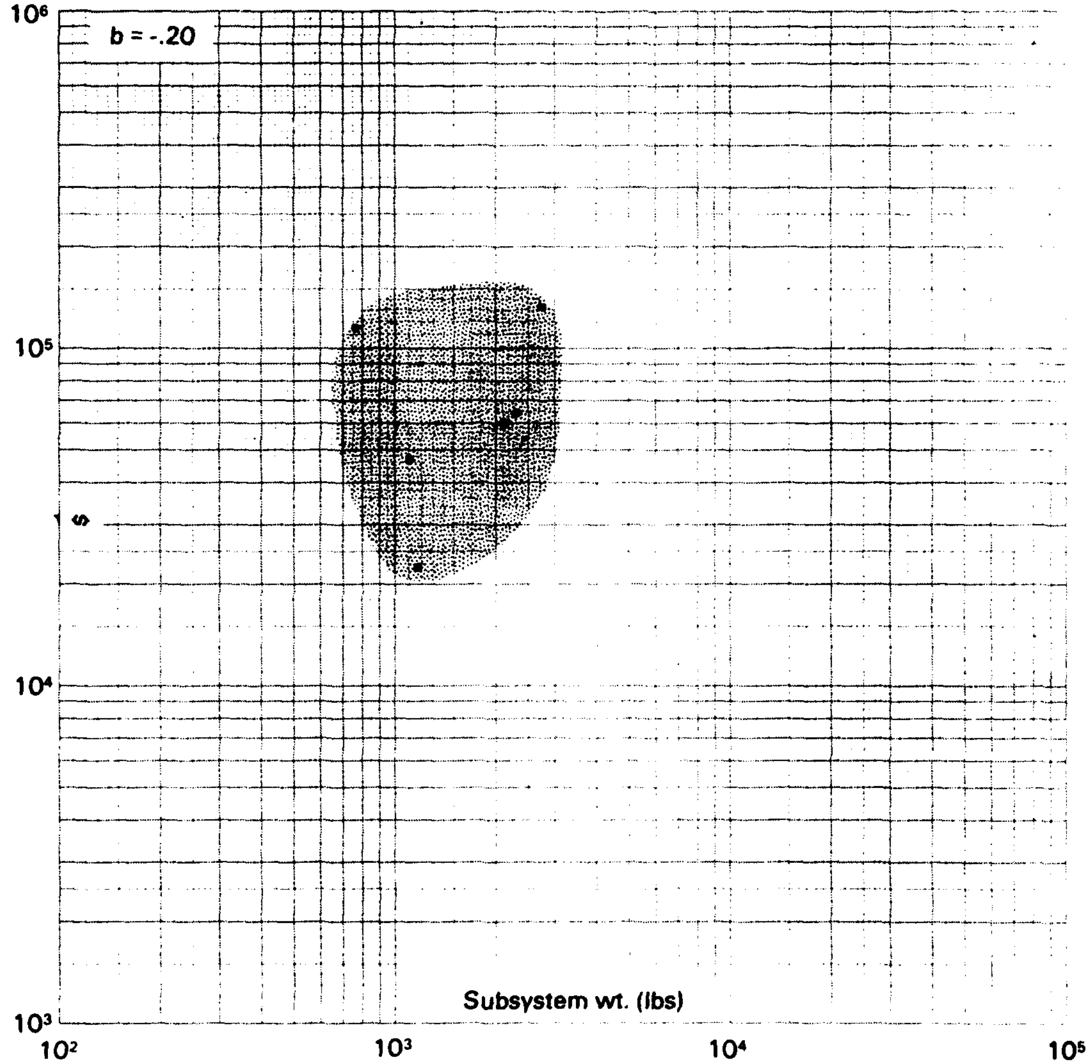


Fig. B-12—Material \$* vs fwd fuselage weight

*100th unit cum ave value

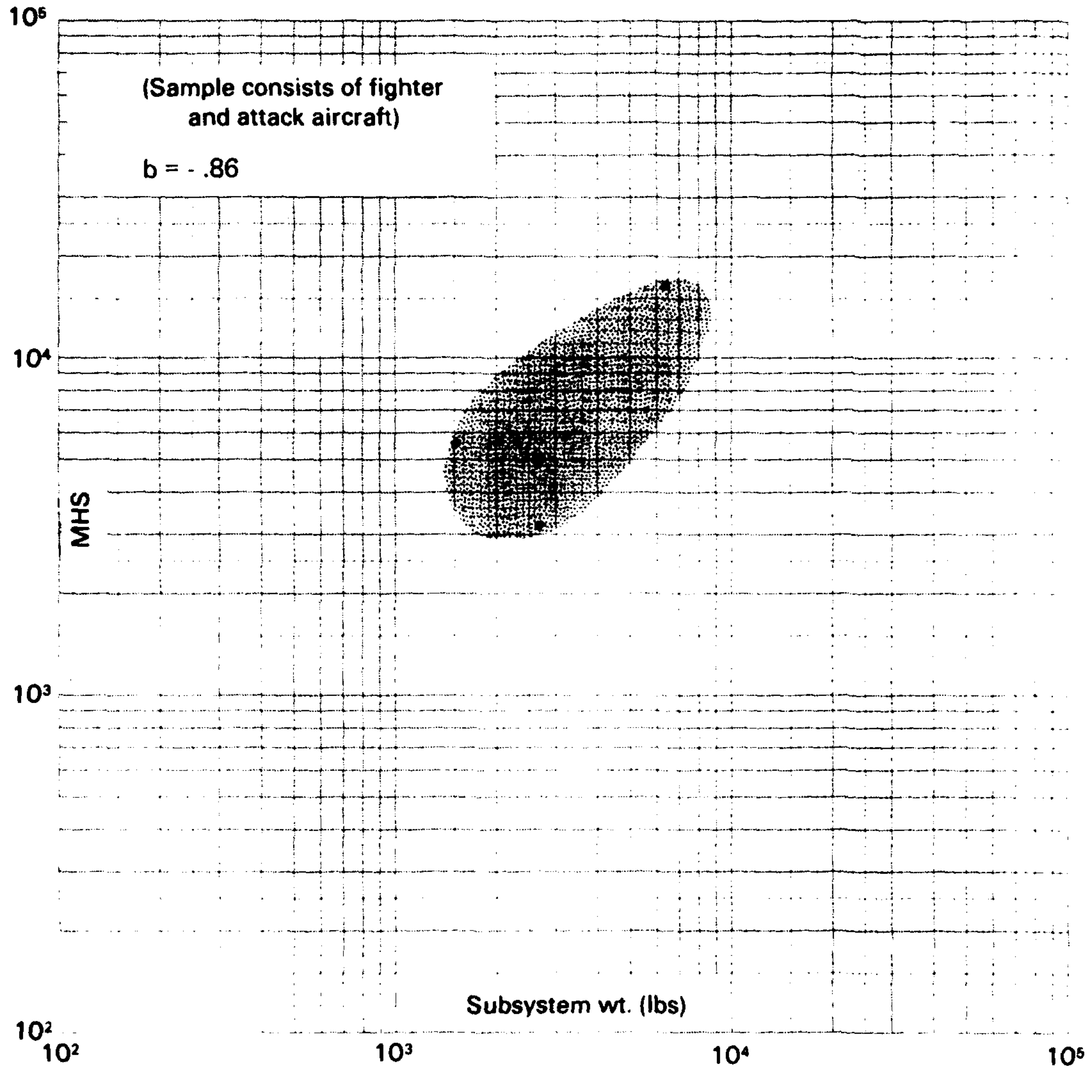


Fig. B-13—Engineering MHS* vs mid fuselage weight

*100th unit cum ave value

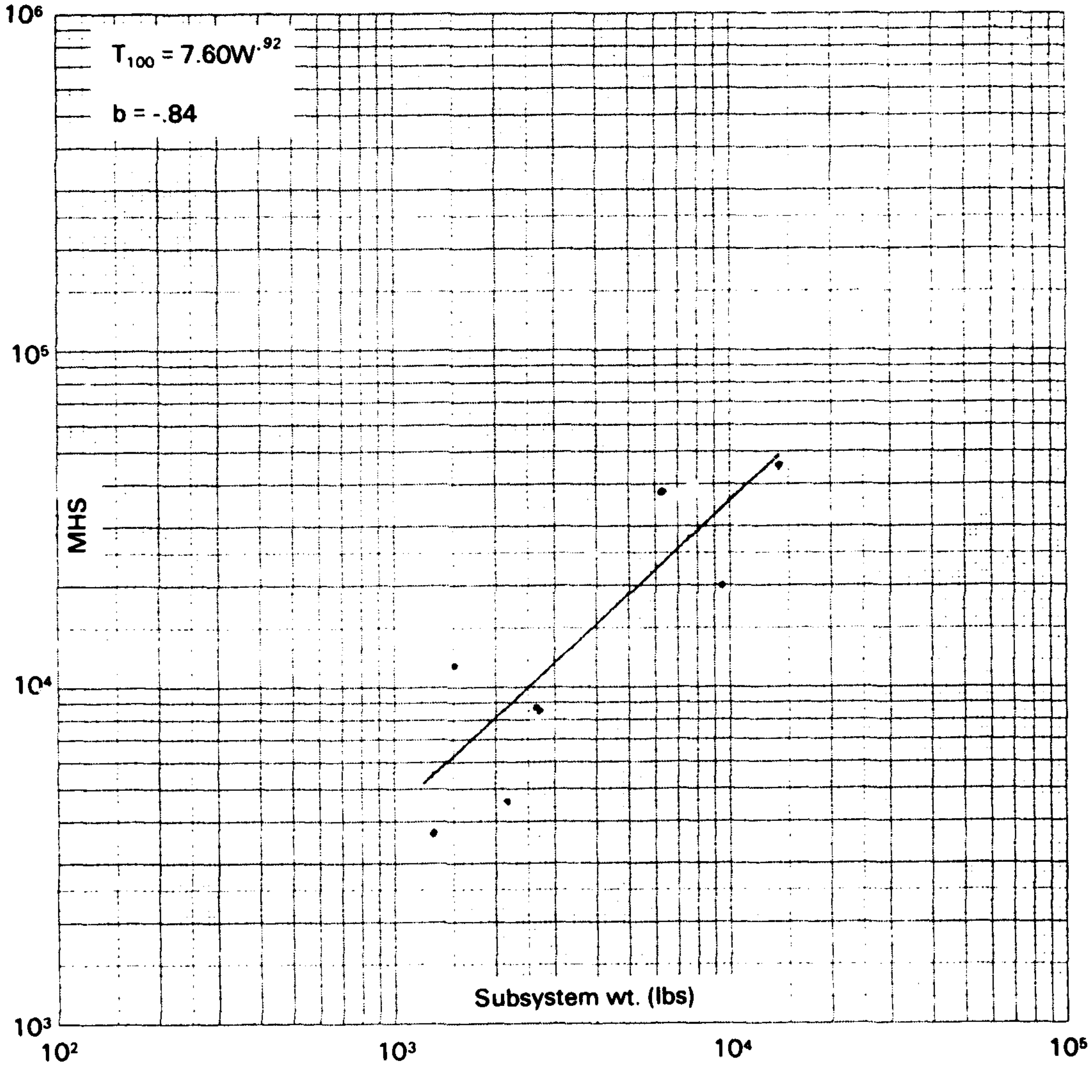


Fig. B-14—Tooling MHS* vs mid fuselage weight

*100th unit cum ave value

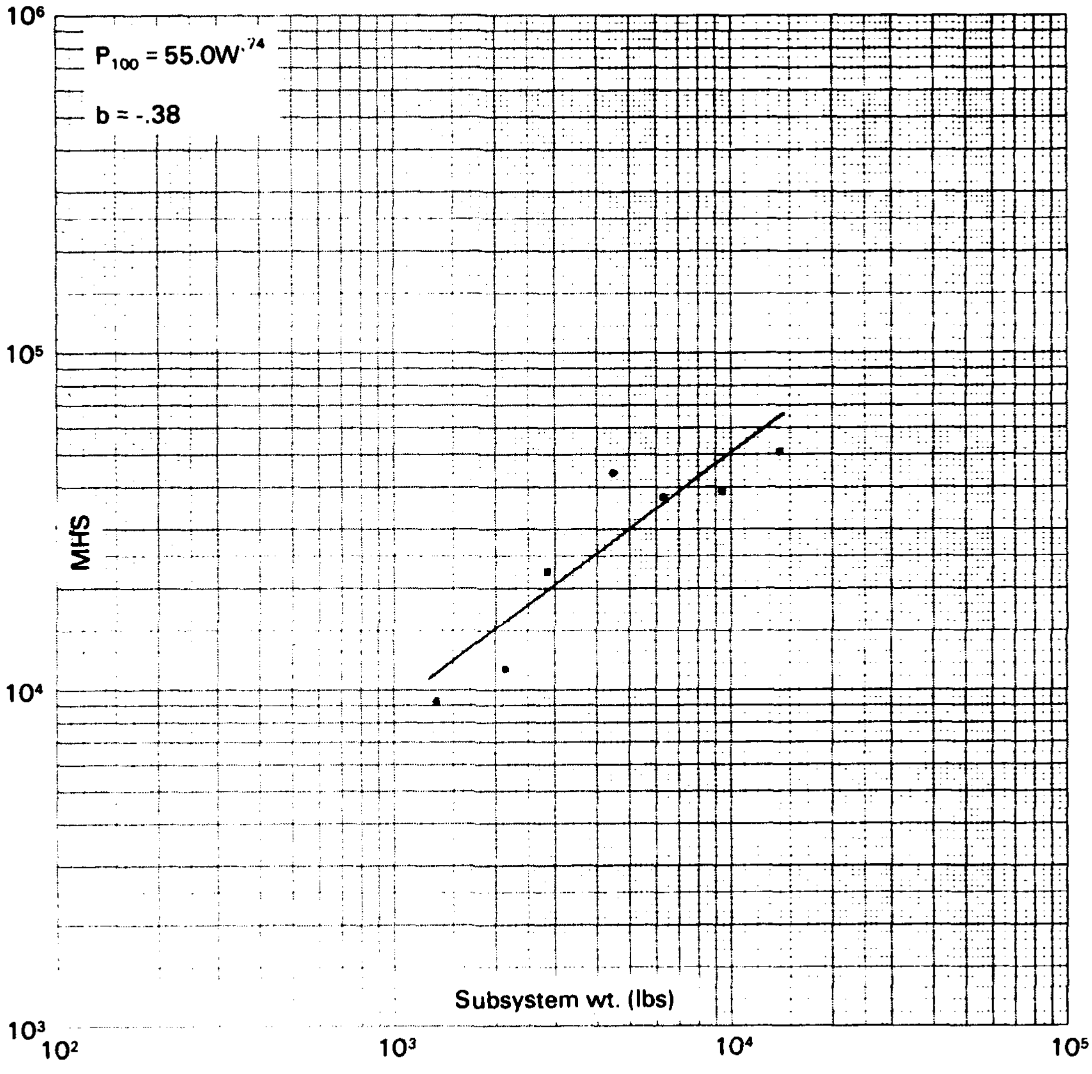


Fig. B-15—Production MHS* vs mid fuselage weight

*100th unit cum ave value

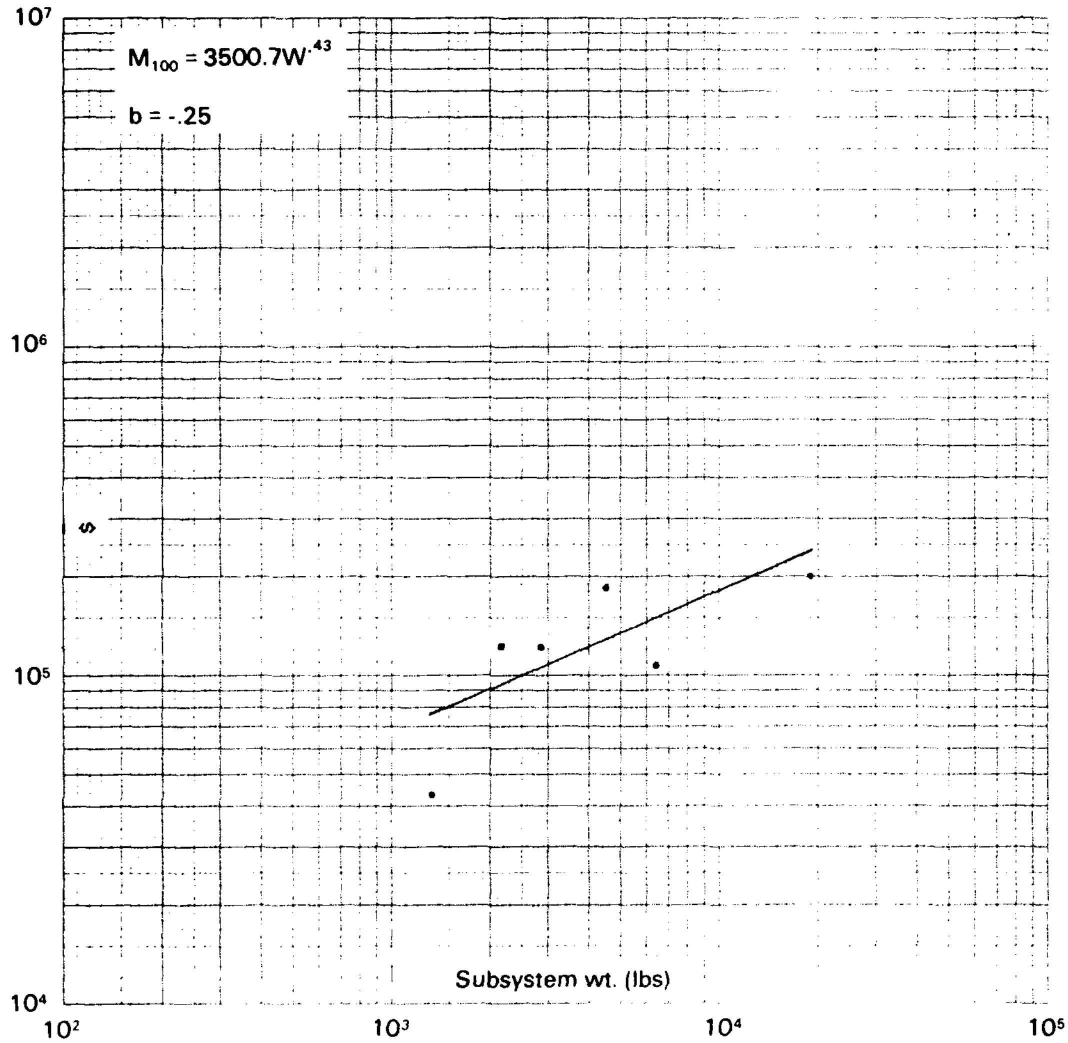


Fig. B-16—Material $* vs mid fuselage weight

*100th unit cum ave value

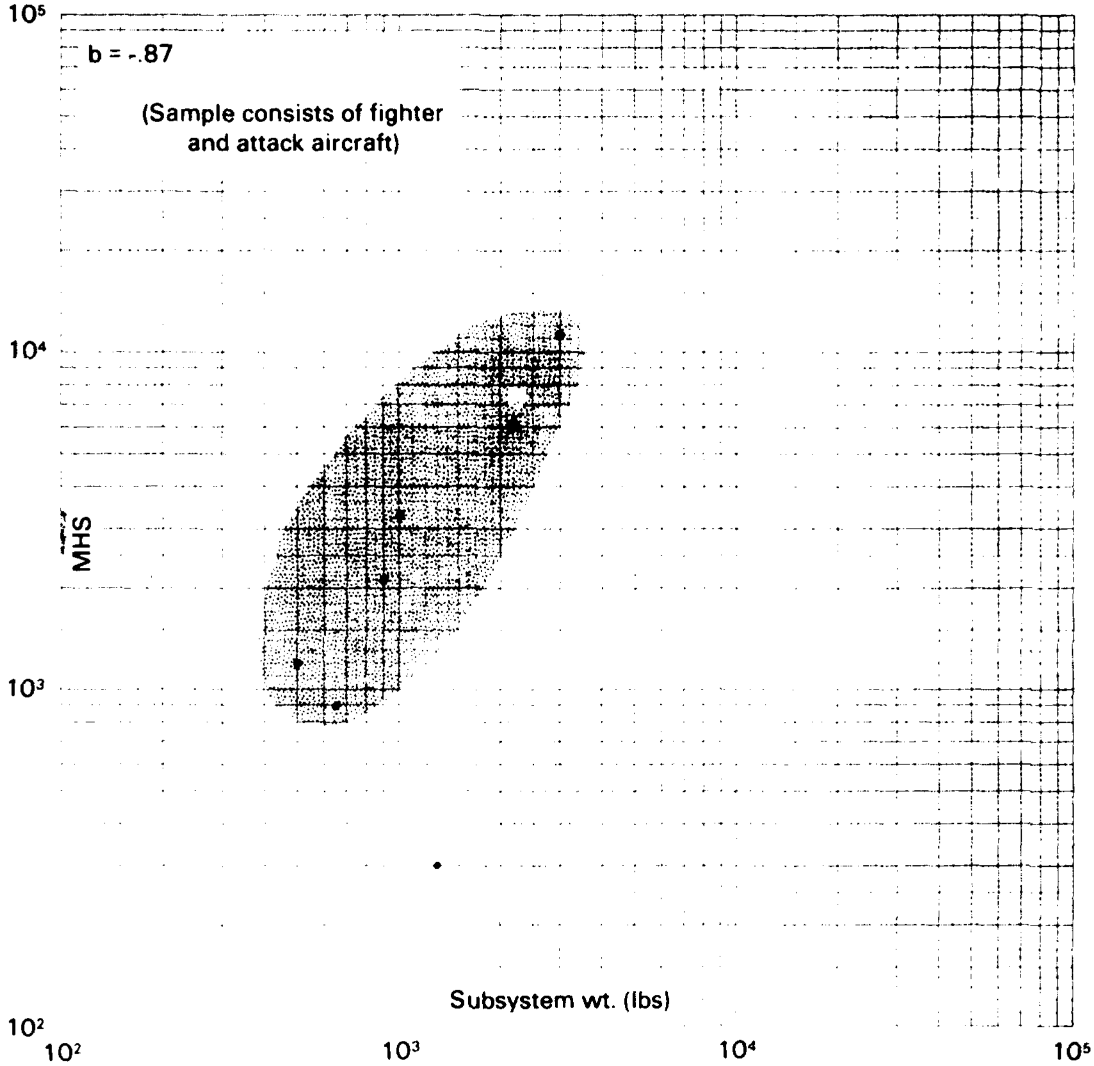


Fig. B-17—Engineering MHS* vs aft fuselage weight

*100th unit cum ave value

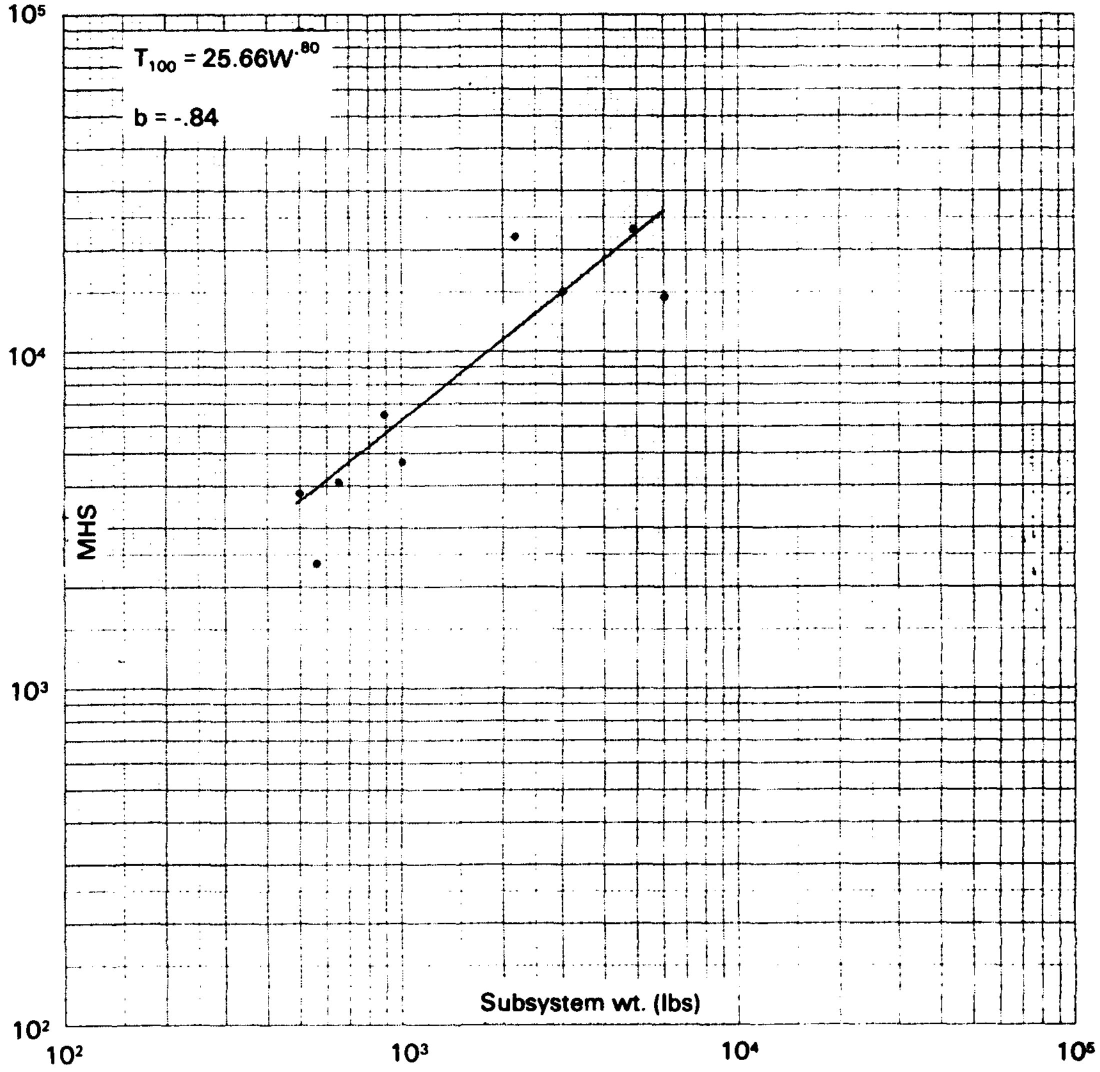


Fig. B-18—Tooling MHS* vs aft fuselage weight

*100th unit cum ave value

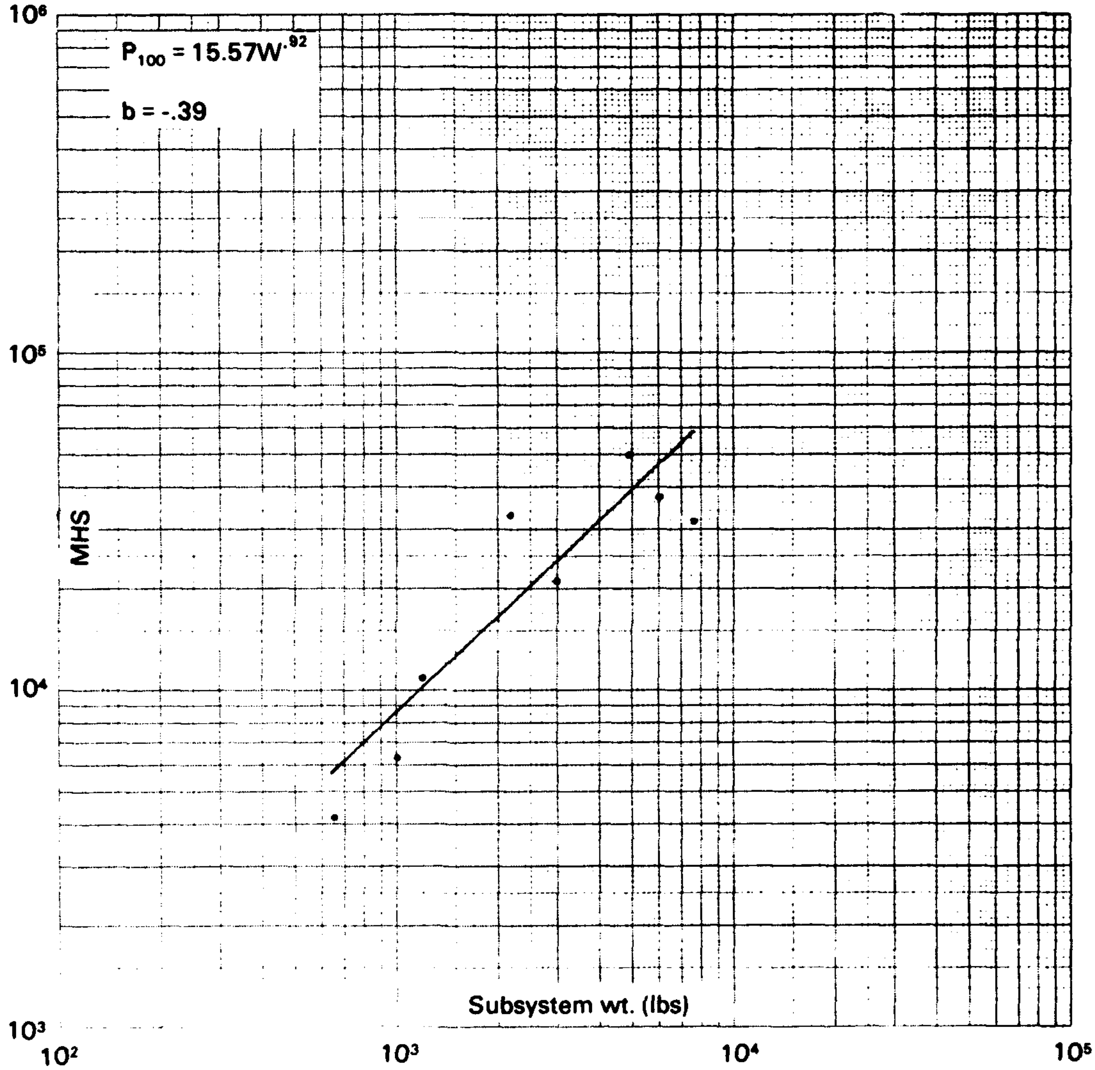


Fig. B-19—Production MHS* vs aft fuseIage weight

*100th unit cum ave value

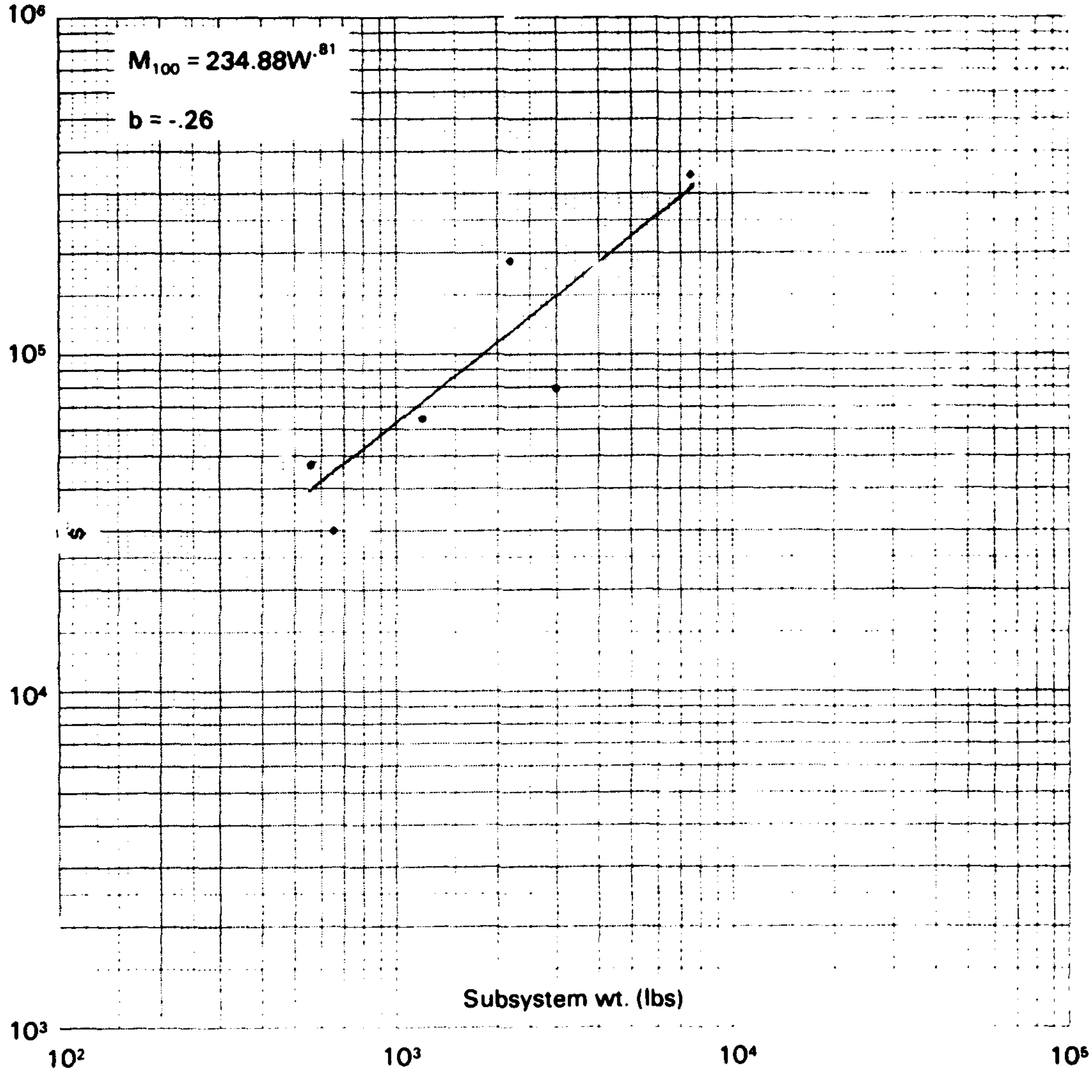


Fig. B-20—Material $* vs aft fuselage weight

*100th unit cum ave value

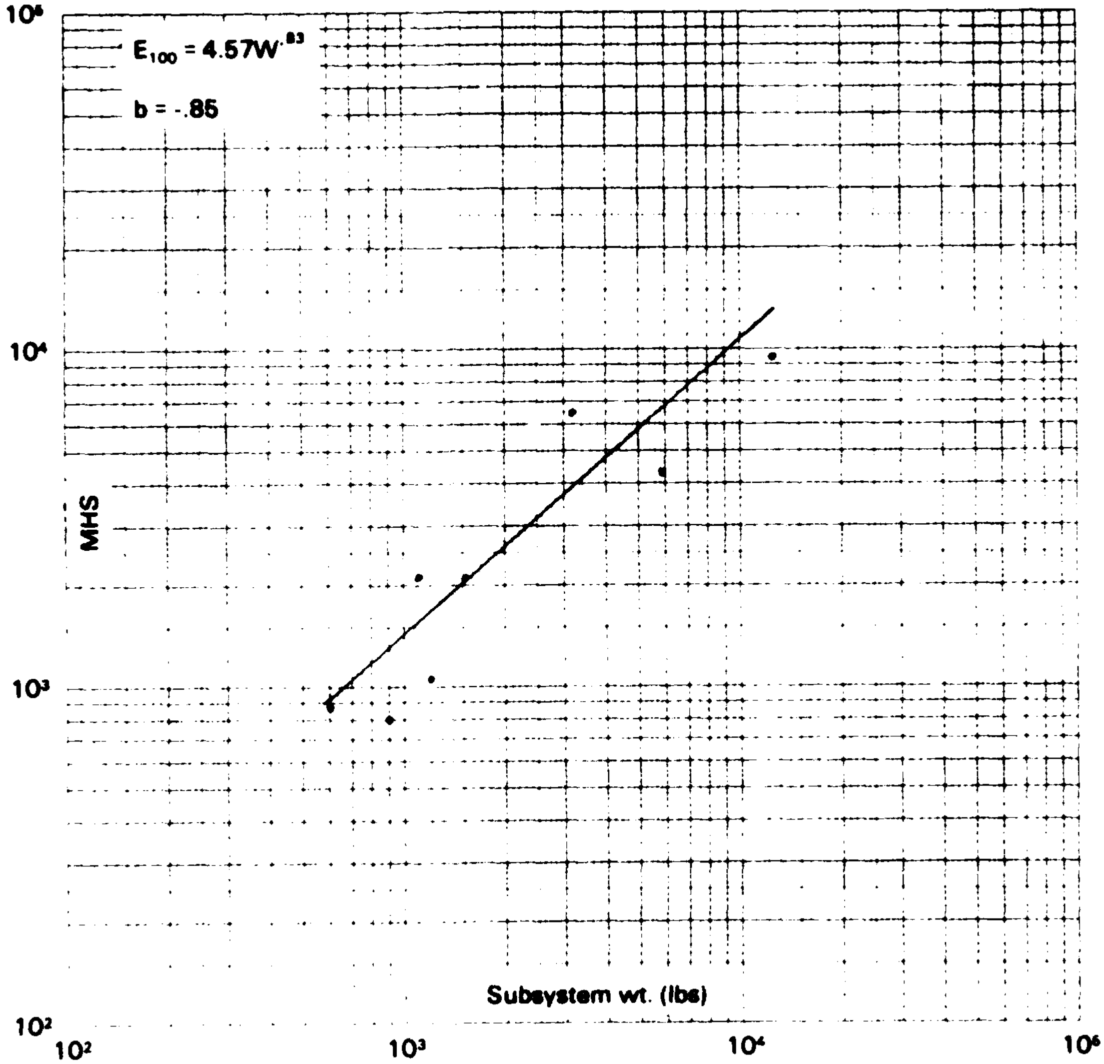


Fig. B-21—Engineering MHS* vs empennage weight

*100th unit cum ave value

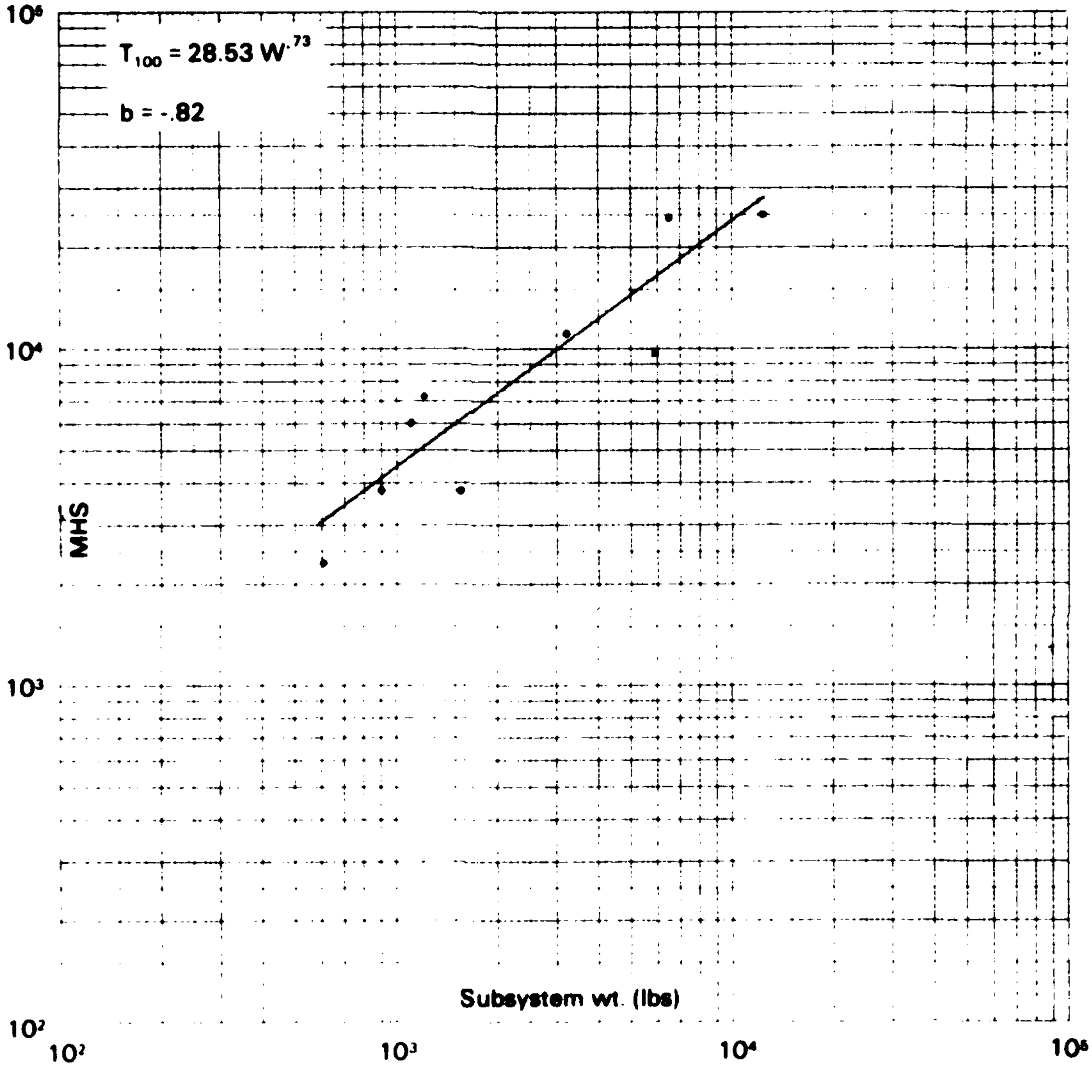


Fig. B-22—Tooling MHS* vs empennage weight

*100th unit cum ave value

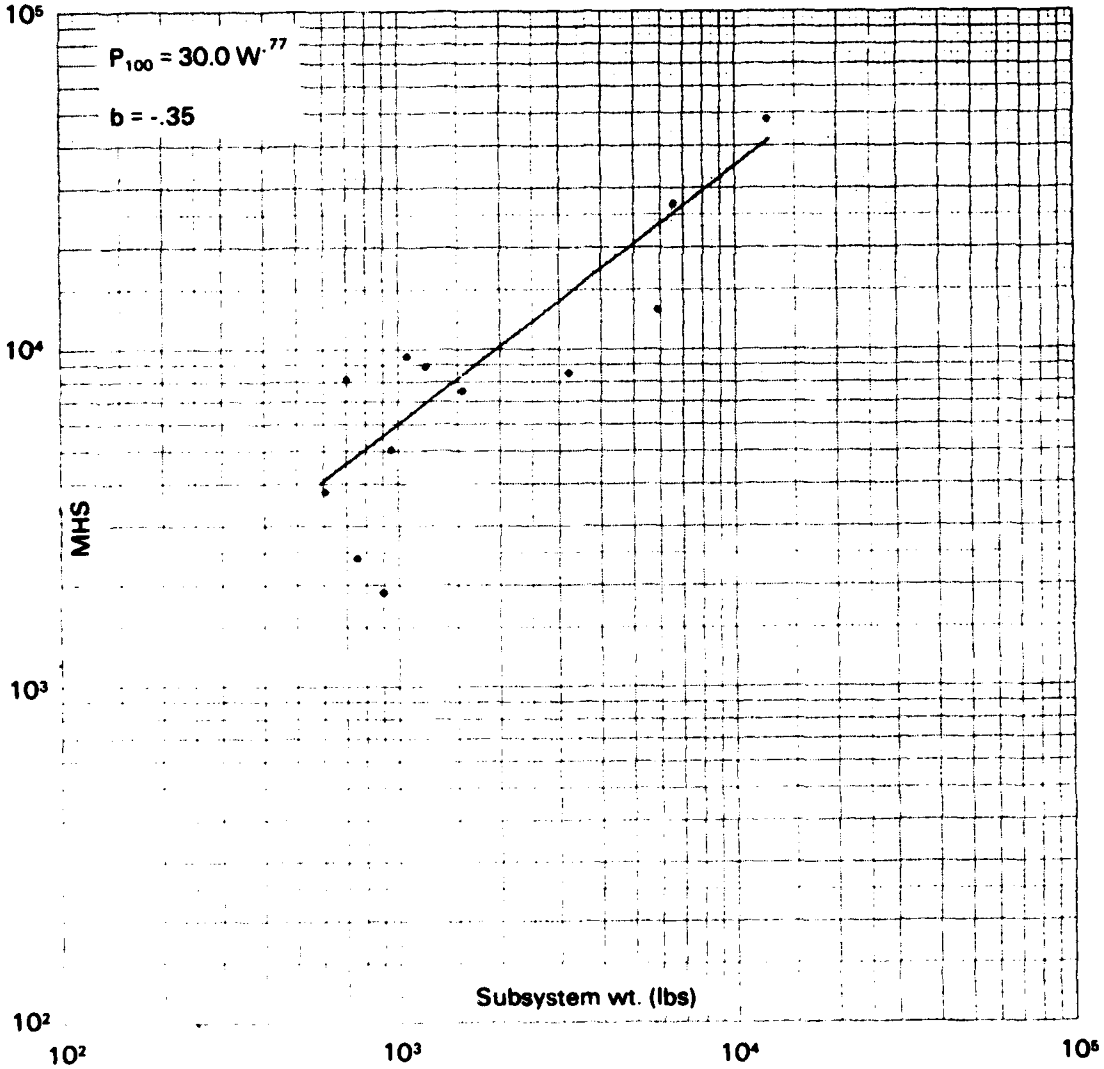


Fig. B-23—Production MHS* vs empennage weight

*100th unit cum ave value

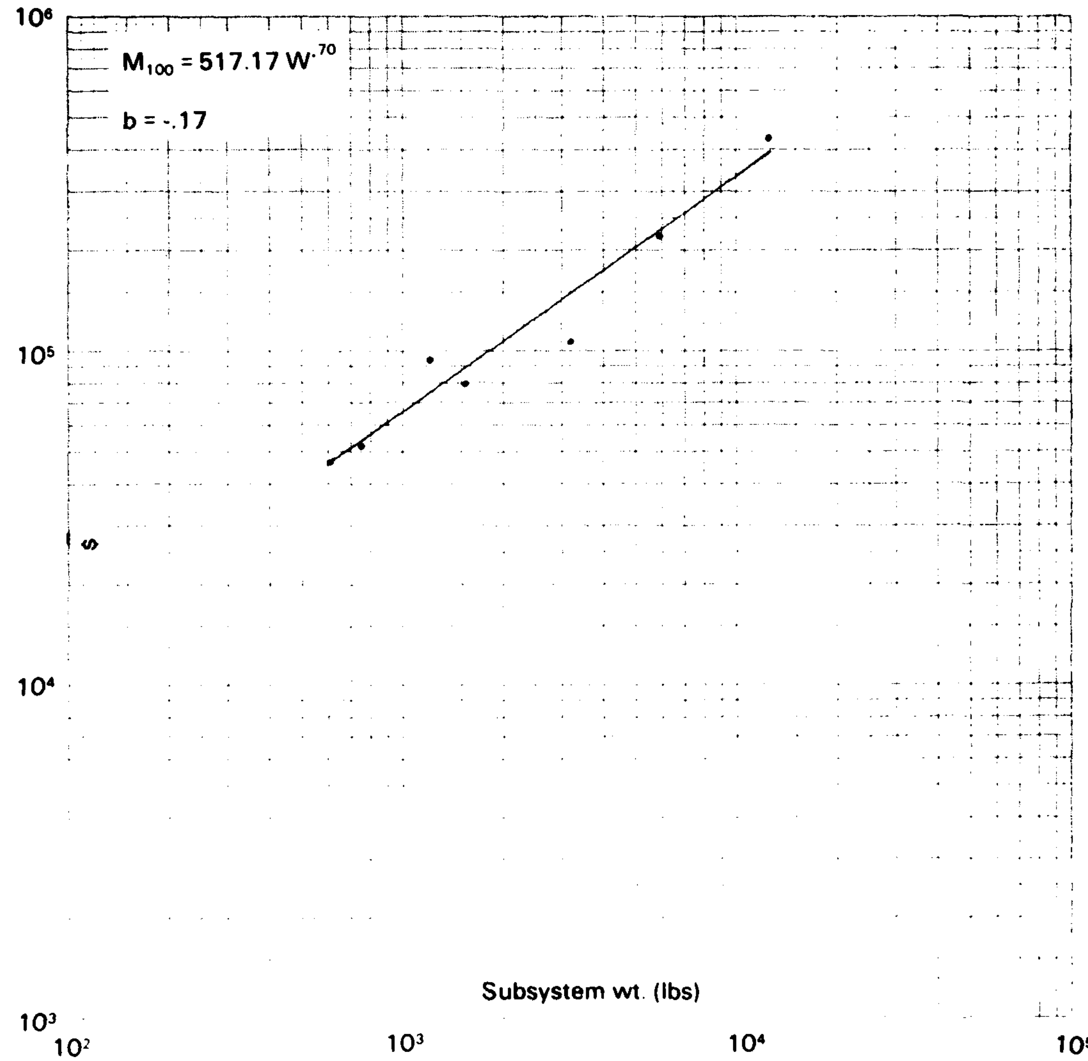


Fig. B-24—Material $* vs empennage weight

*100th unit cum ave value

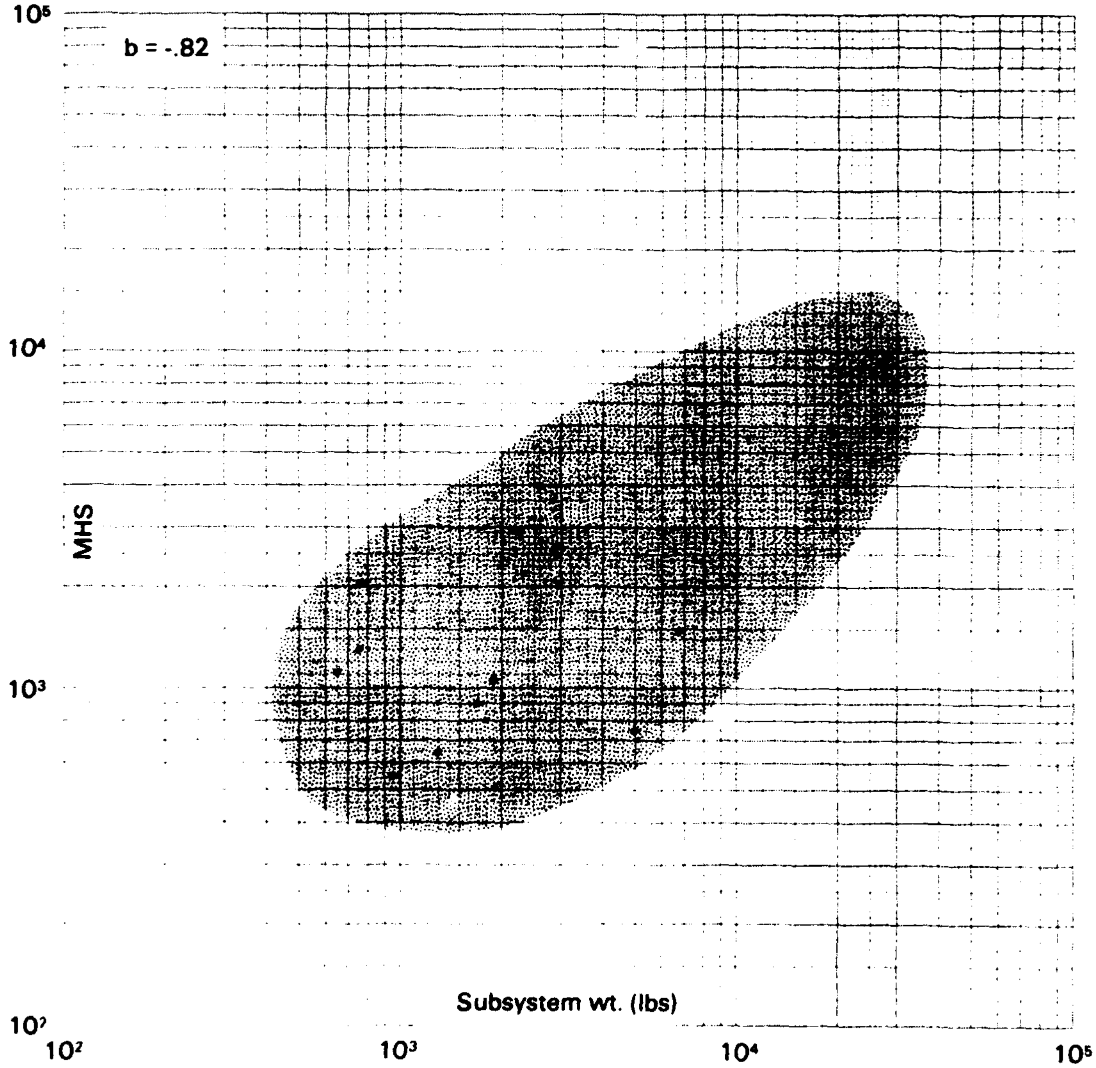


Fig. B-25—Engineering MHS* vs landing gear weight

*100th unit cum ave value

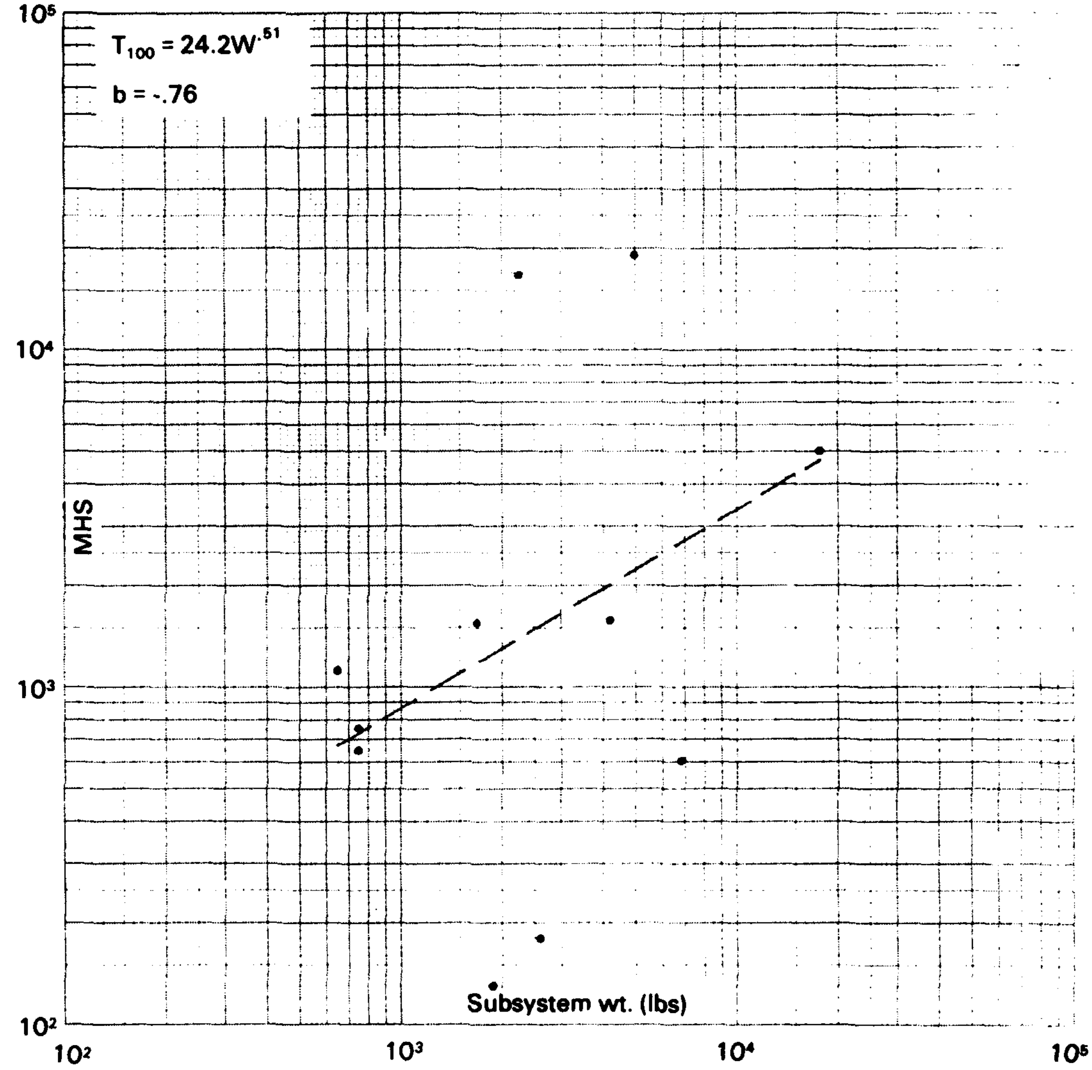


Fig. B-26—Tooling MHS* vs landing gear weight

*100th unit cum ave value

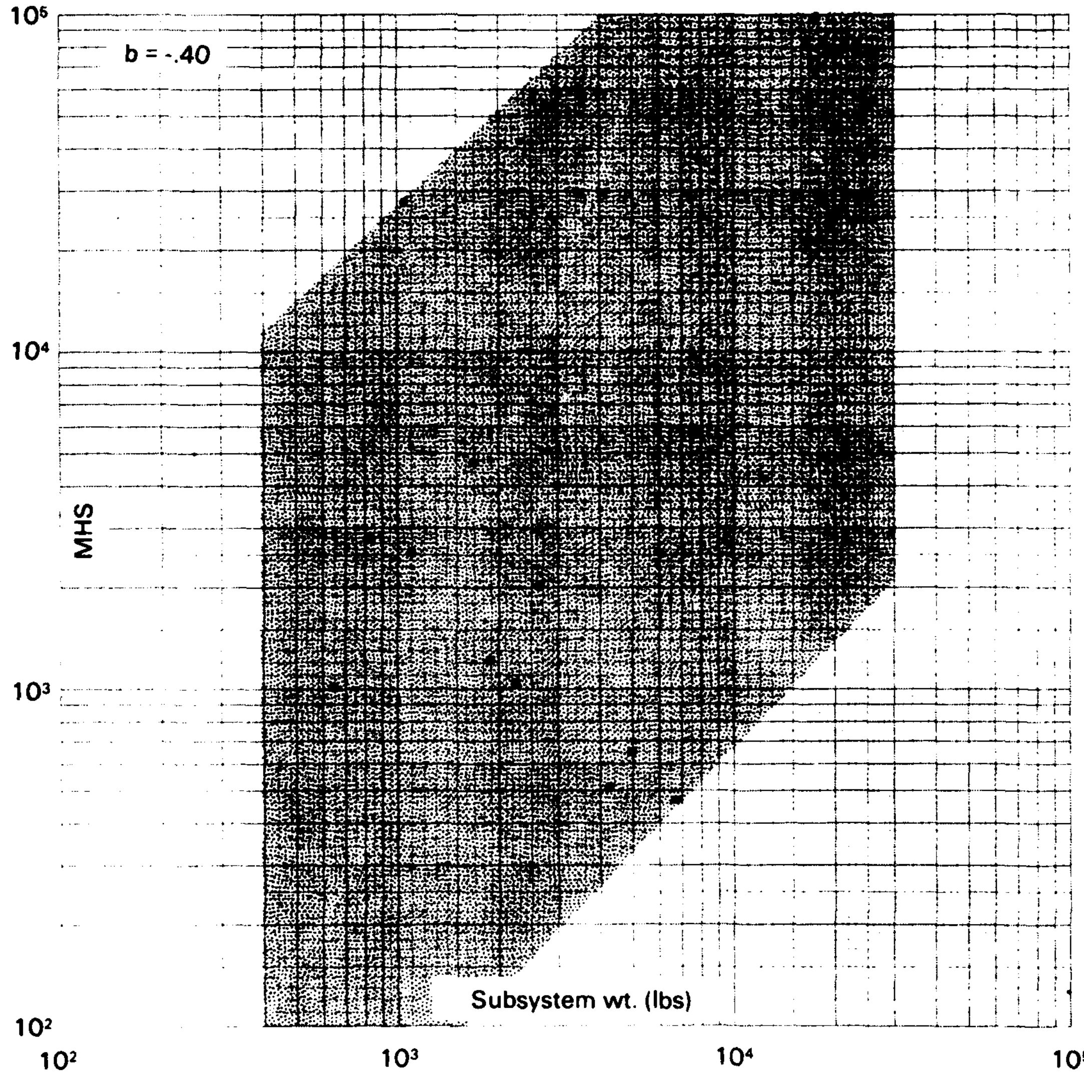


Fig. B-27—Production MHS* vs landing gear weight

*100th unit cum ave value

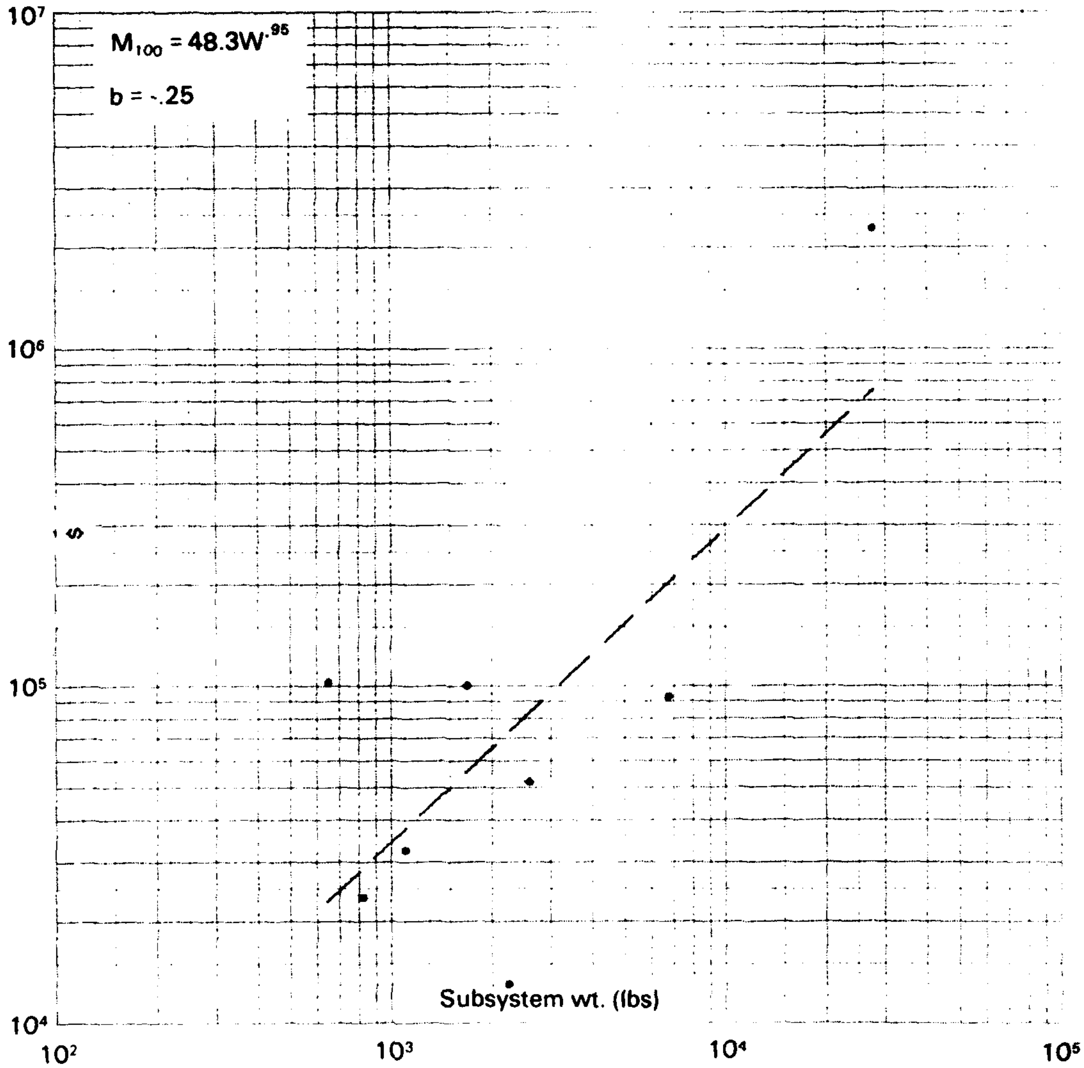


Fig. B-28—Material \$* vs landing gear weight

*100th unit cum ave value

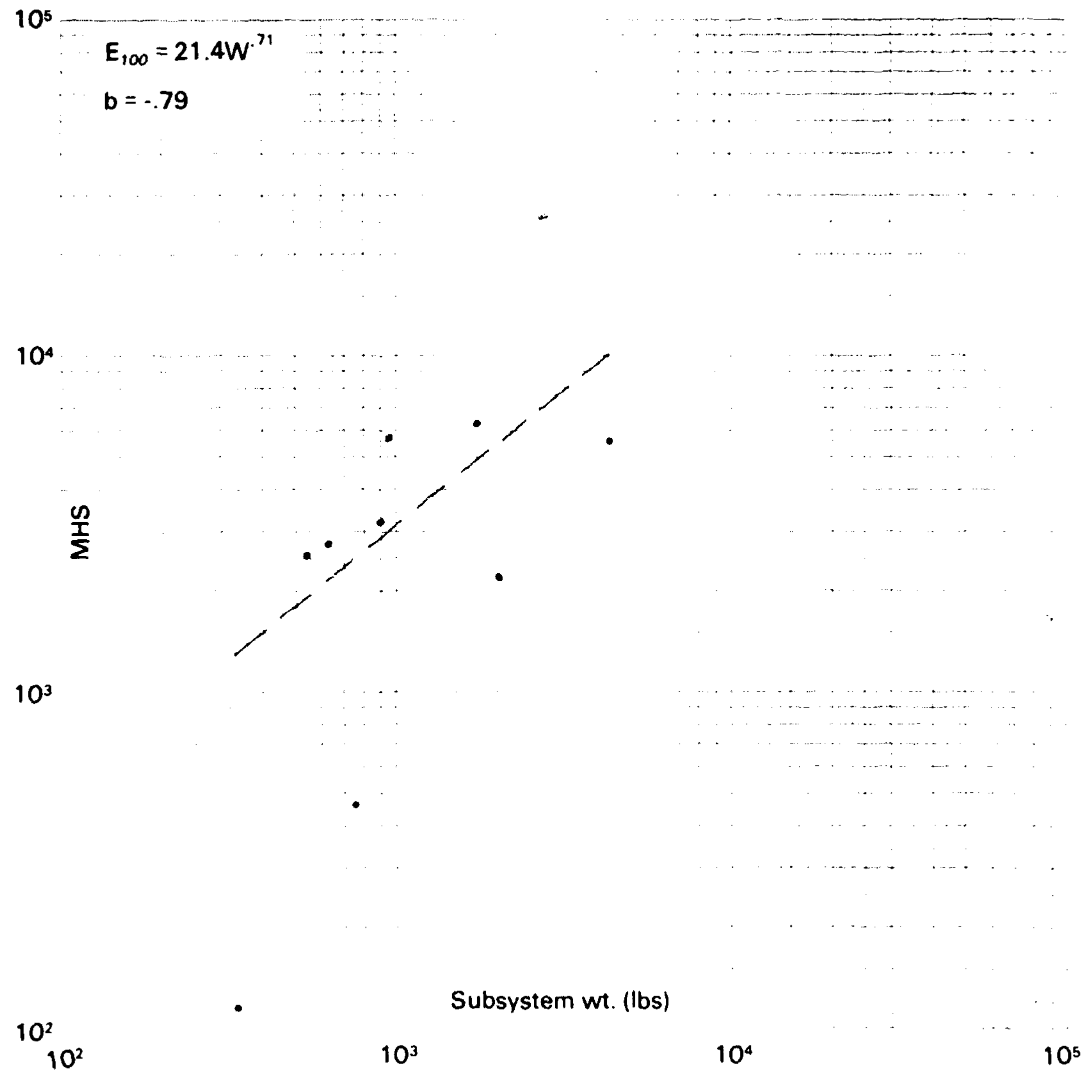


Fig. B-29—Engineering MHS* vs electrical system weight

*100th unit cum ave value

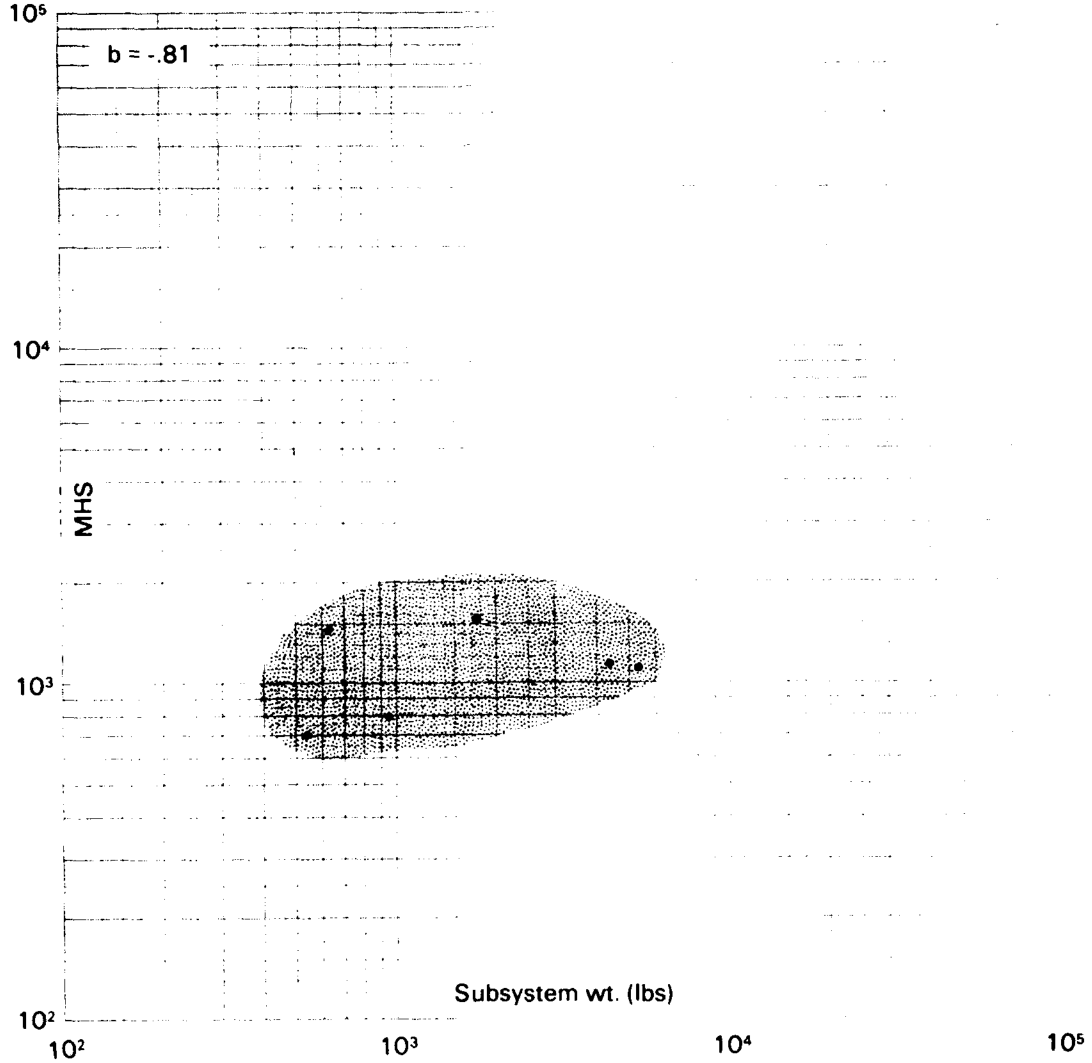


Fig. B-30—Tooling MHS* vs electrical system weight

*100th unit cum ave value

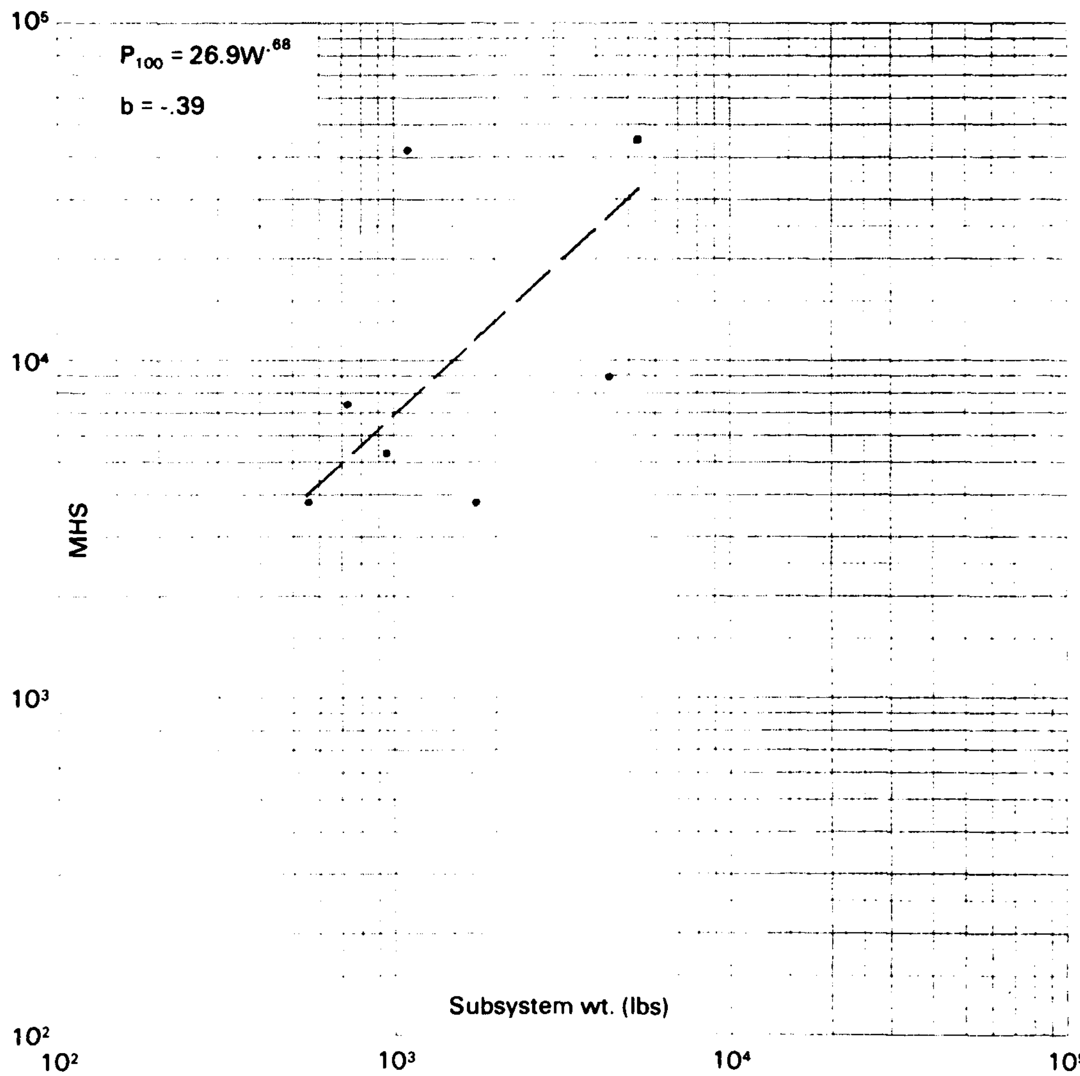
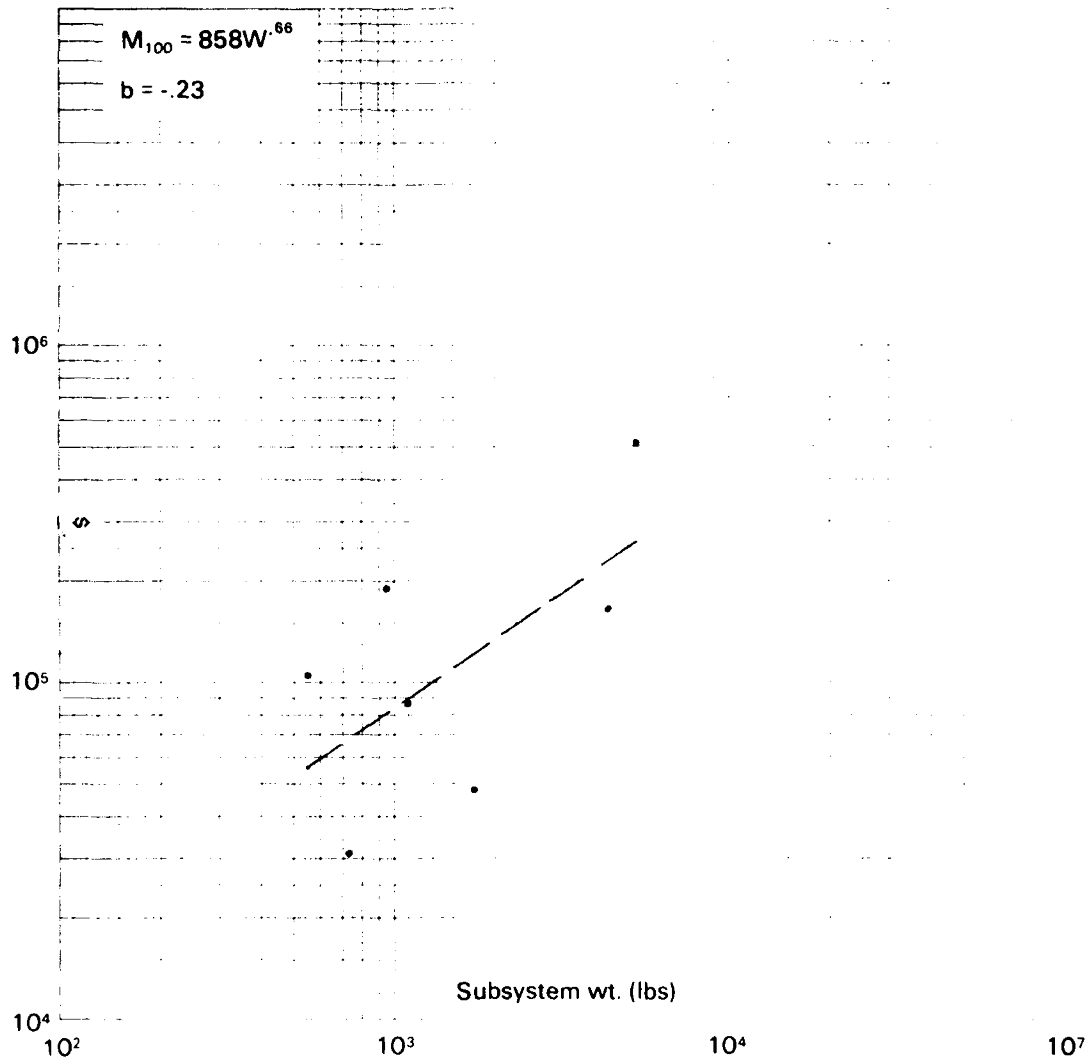


Fig. B-31—Production MHS* vs electrical system weight

*100th unit cum ave value



B-32—Material $* vs electrical system weight

*100th unit cum ave value

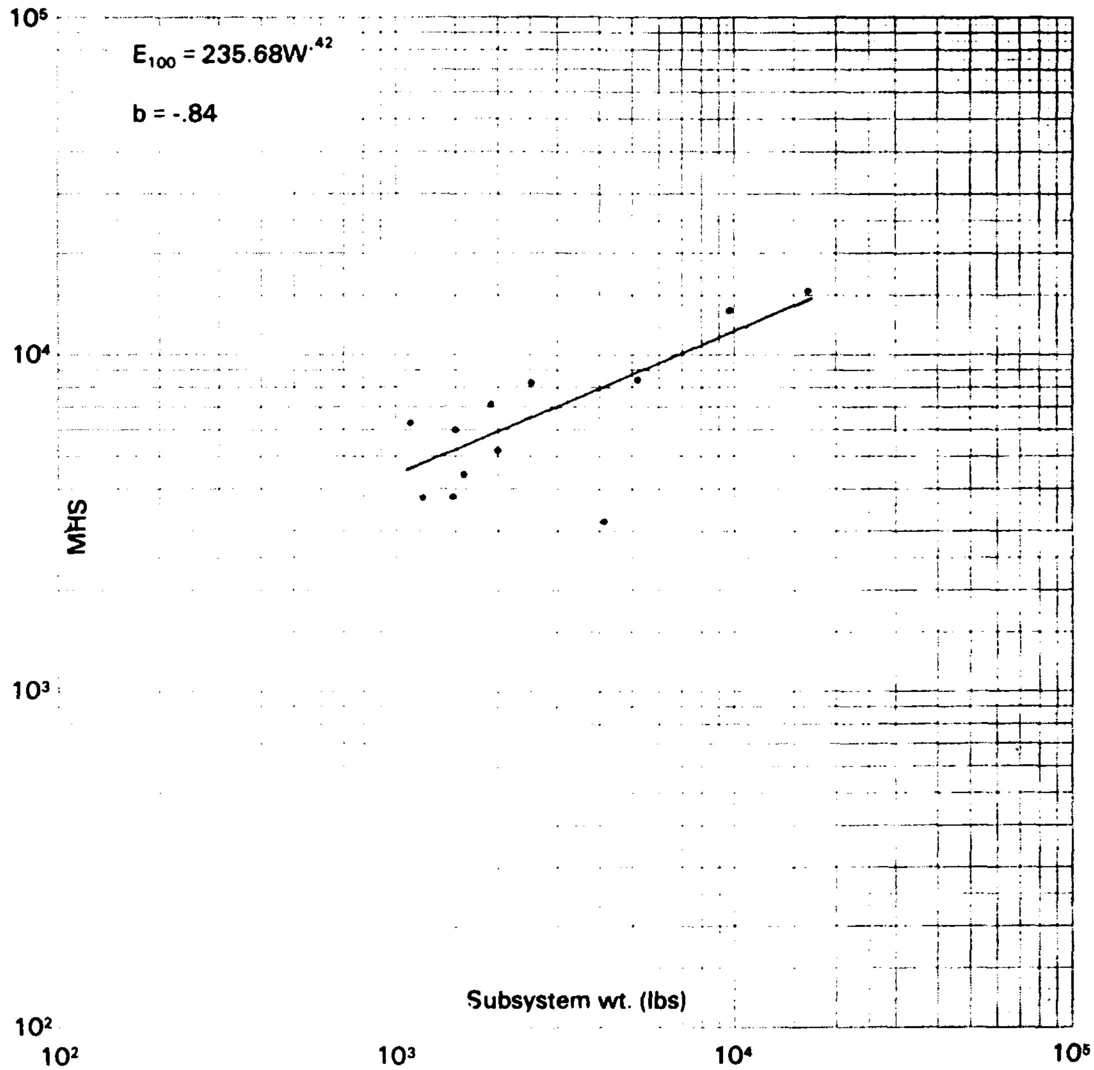


Fig. B-33—Engineering MHS* vs controls/hy: .ulic weight

**100th unit cum ave value*

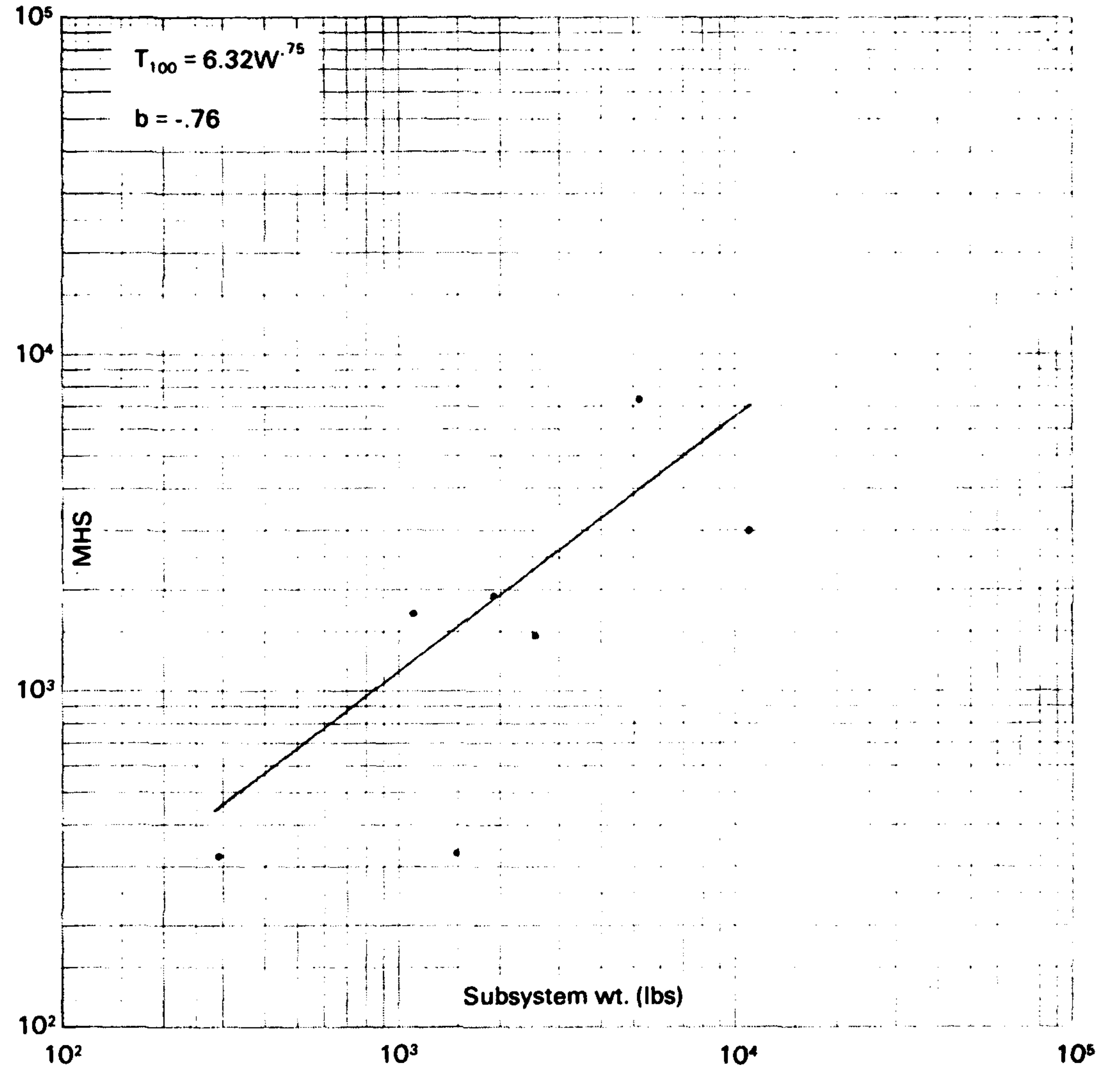


Fig. B-34—Tooling MHS* vs control/hydraulics weight

*100th unit cum ave value

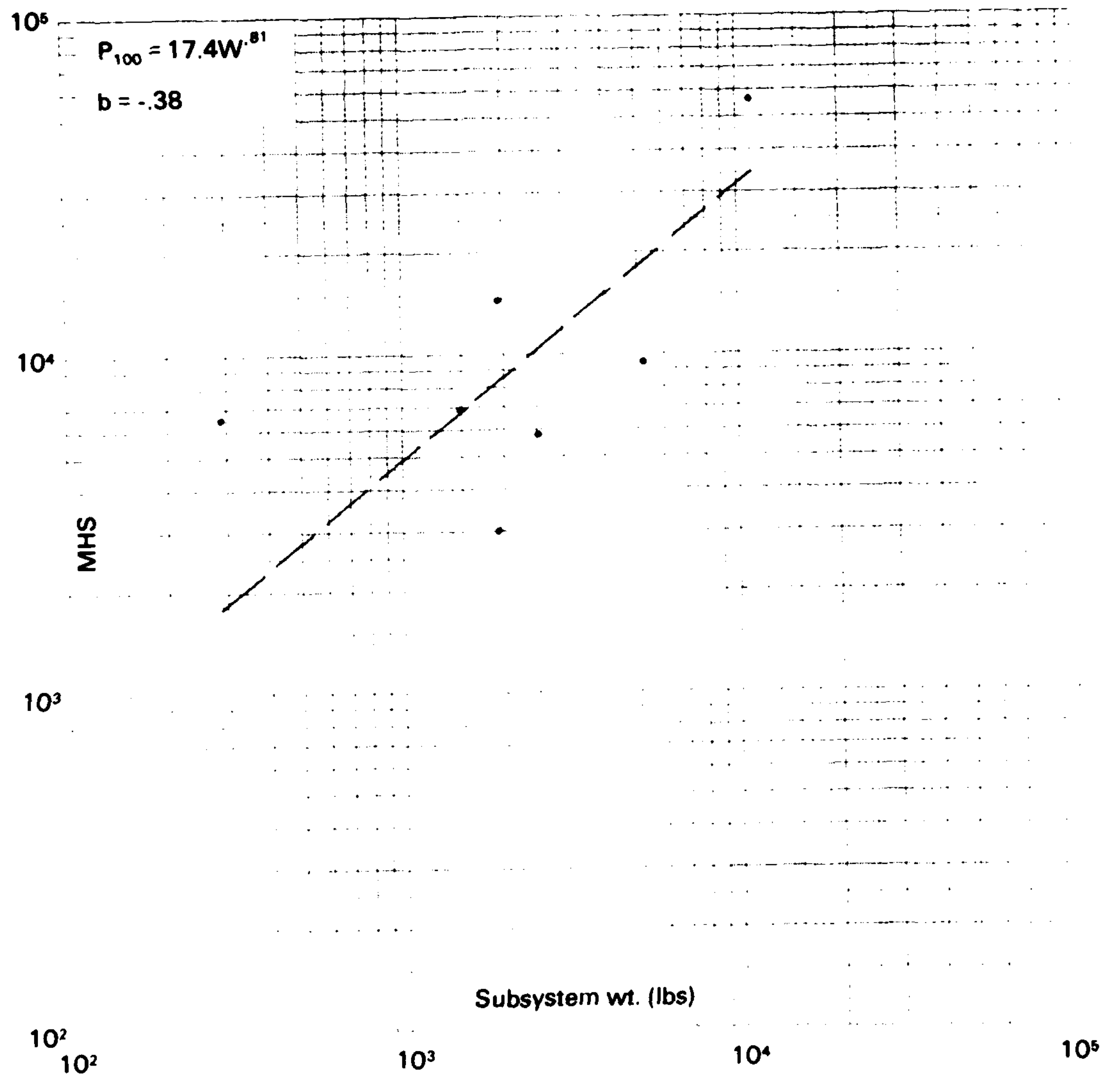


Fig. B-35—Production MHS* vs control/hydraulics weight

*100th unit cum ave value

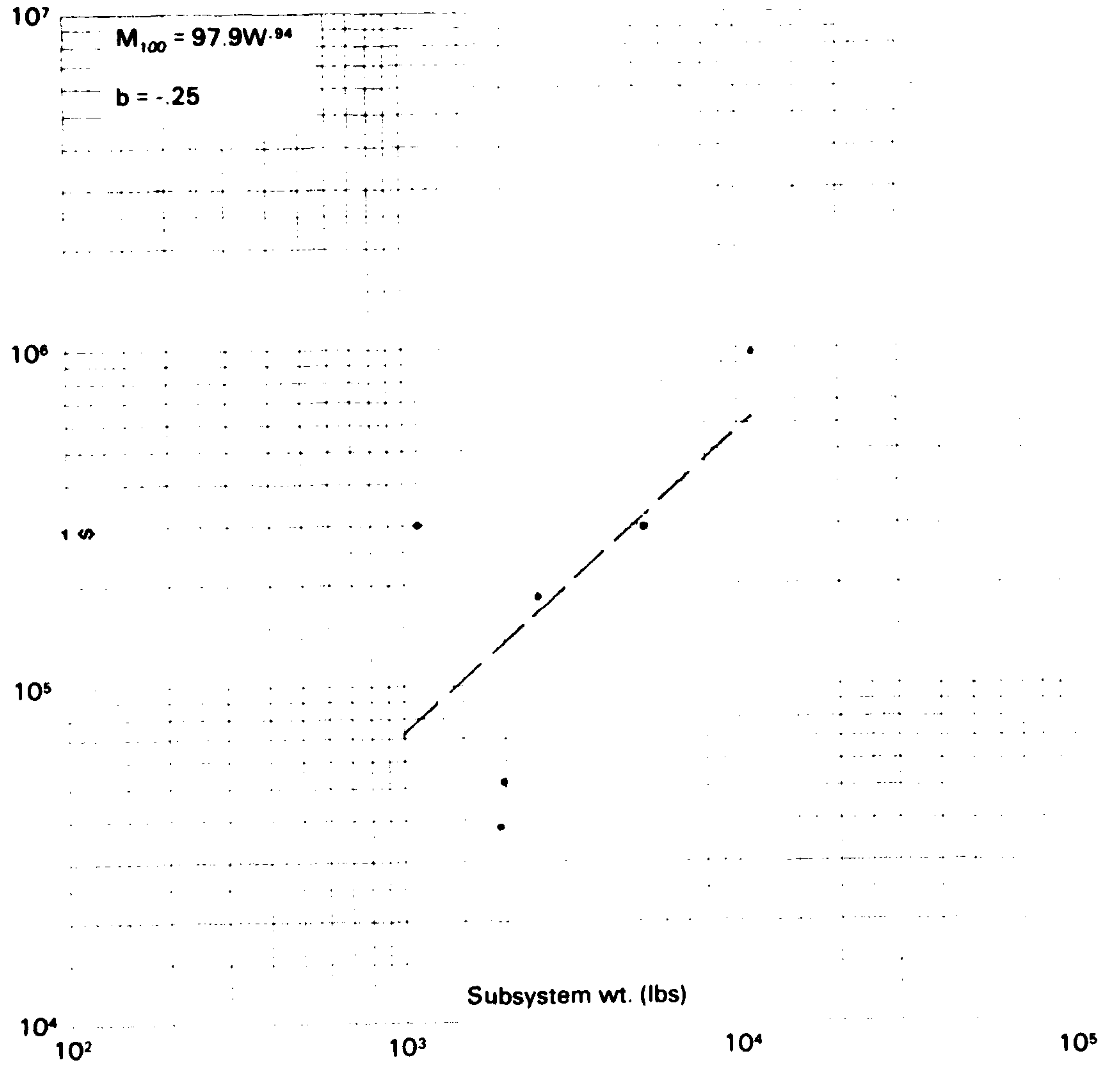


Fig. B-36—Material \$* vs control/hydraulics weight

*100th unit cum ave value

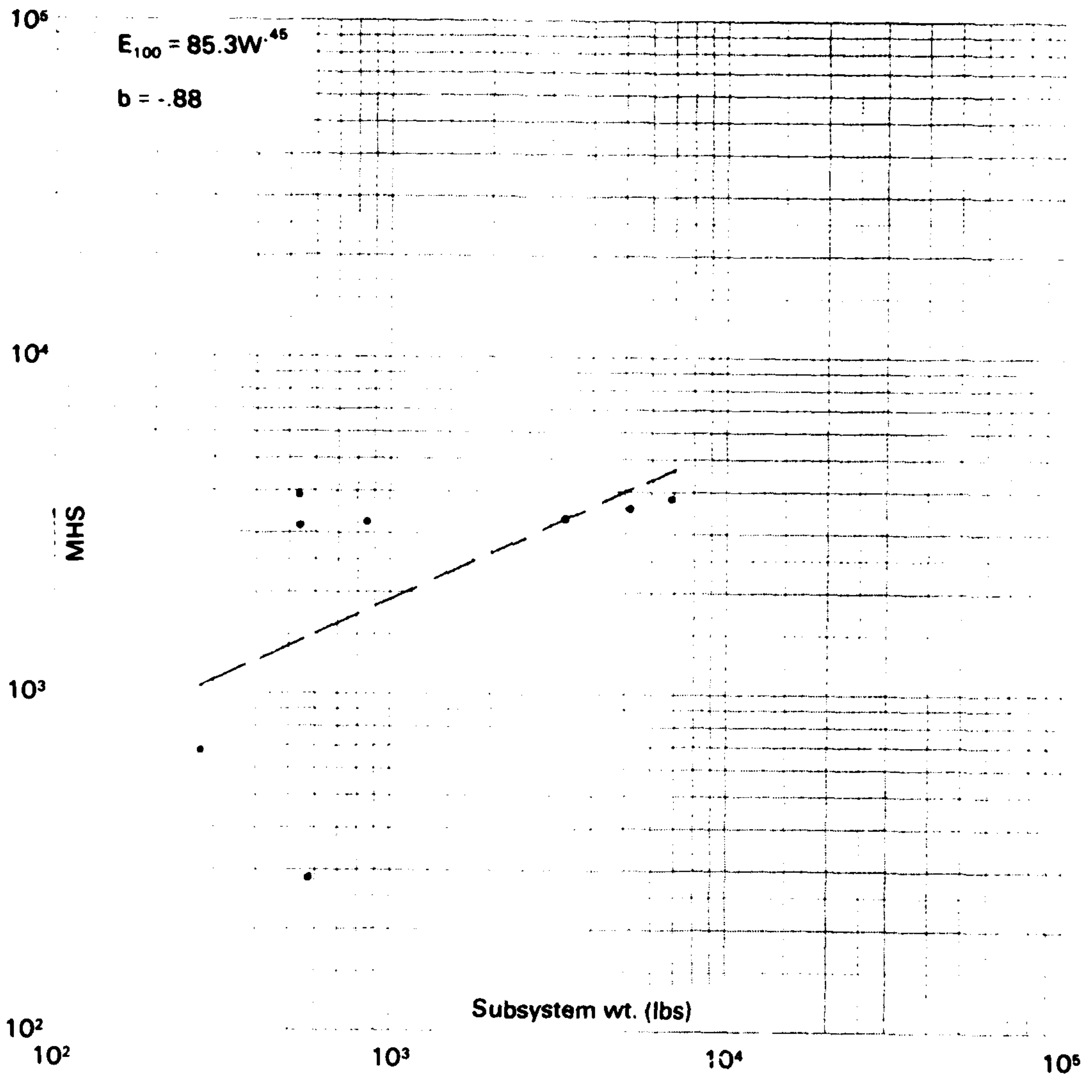


Fig. B-37—Engineering MHS* vs furnishing/equipment weight

*100th unit cum ave value

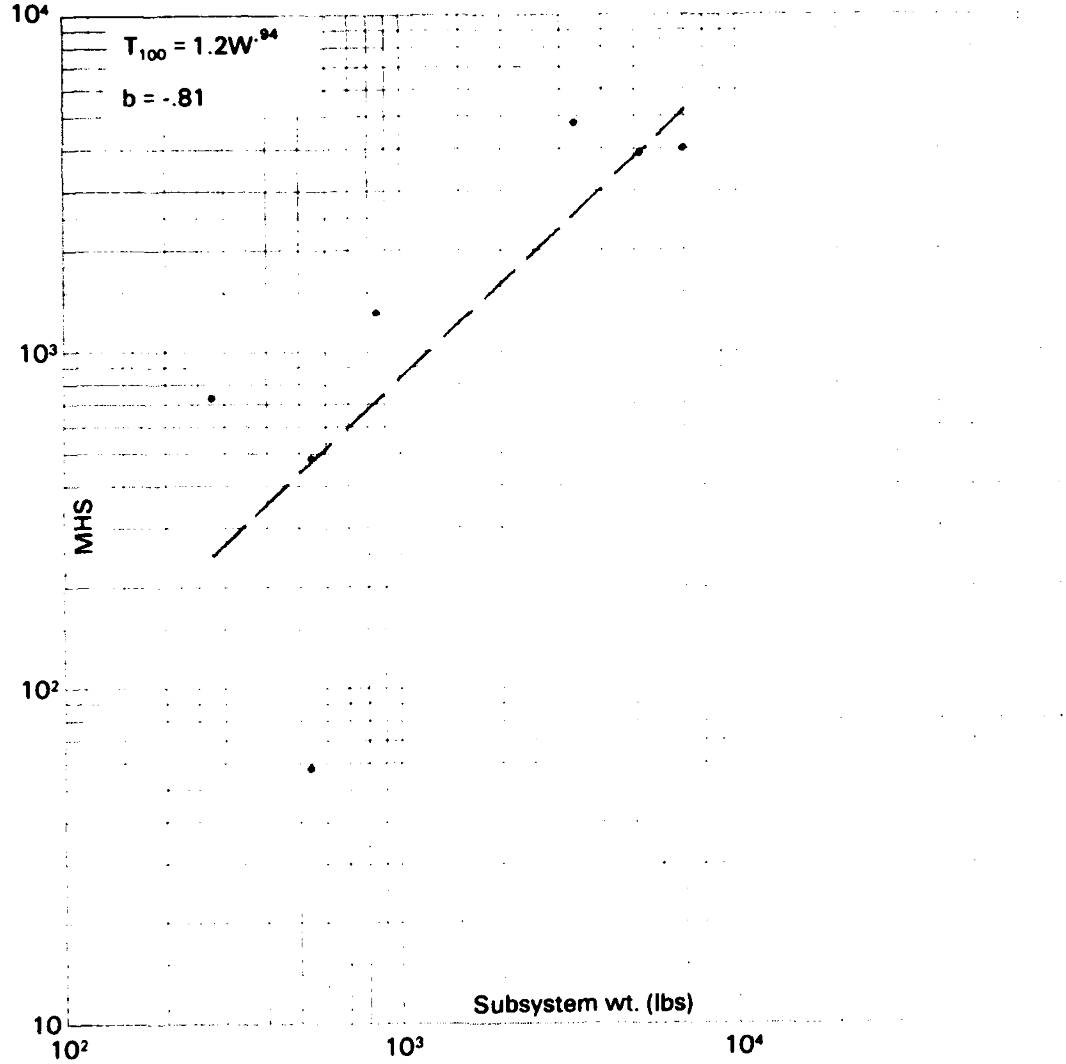


Fig. B-38—Tooling MHS* vs furnishing/equipment weight

*100th unit cum ave value

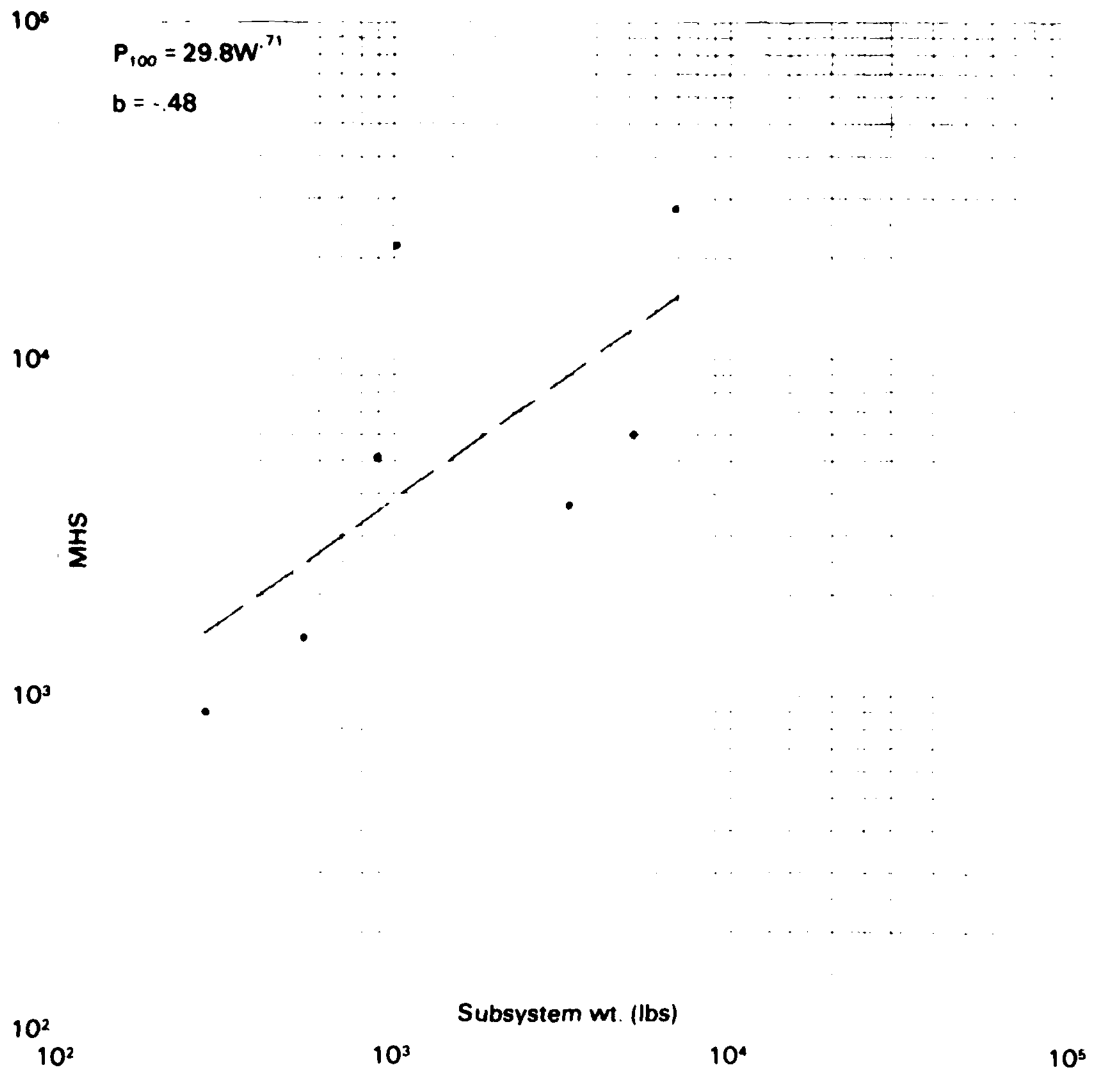


Fig. B-39—Production MHS* vs furnishing/equipment weight

*100th unit cum ave value

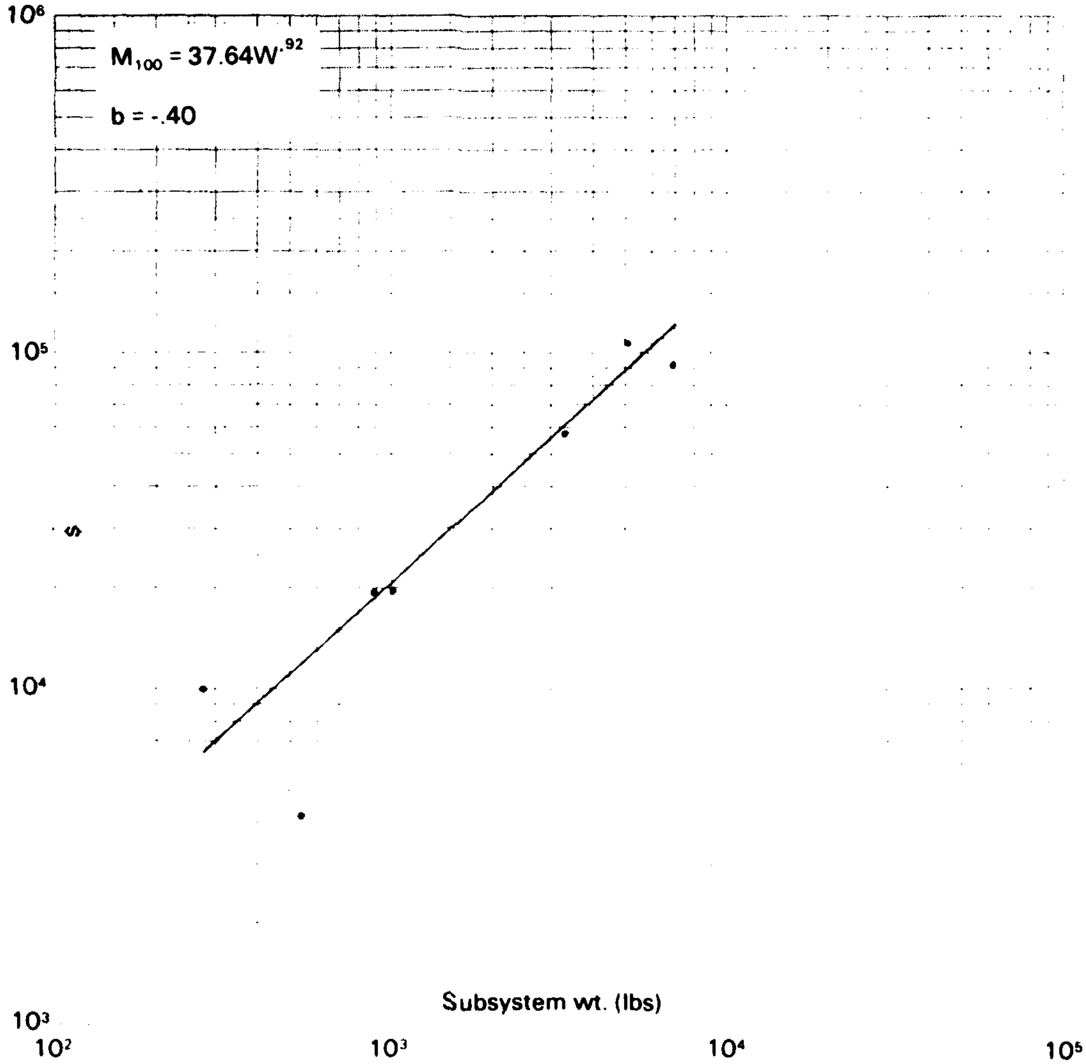


Fig. B-40—Material $* vs furnishing/equipment weight

*100th unit cum ave value

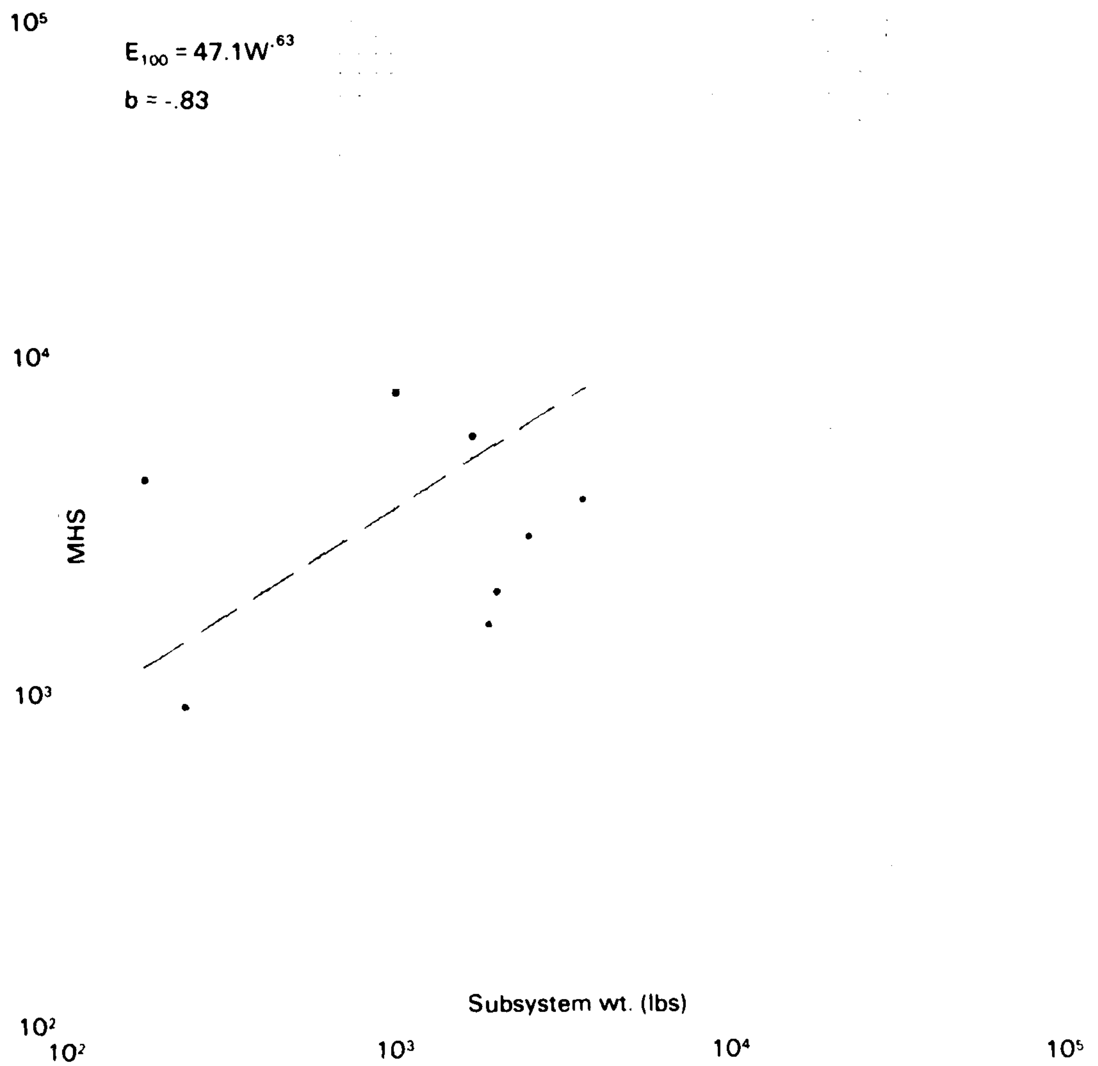


Fig. B-41—Engineering MHS* vs environmental controls weight

*100th unit cum ave value

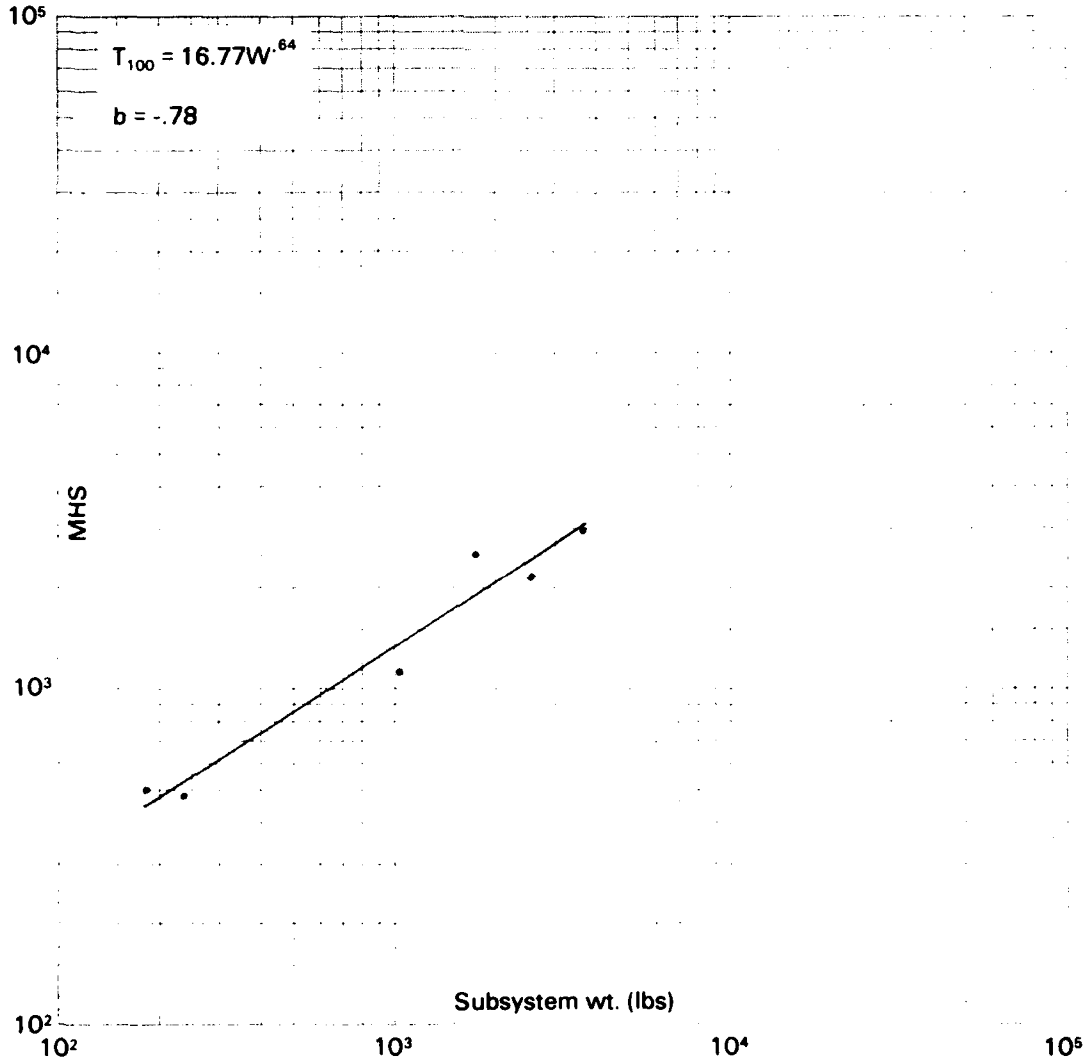


Fig. B-42—Tooling MHS* vs environmental controls weight

*100th unit cum ave value

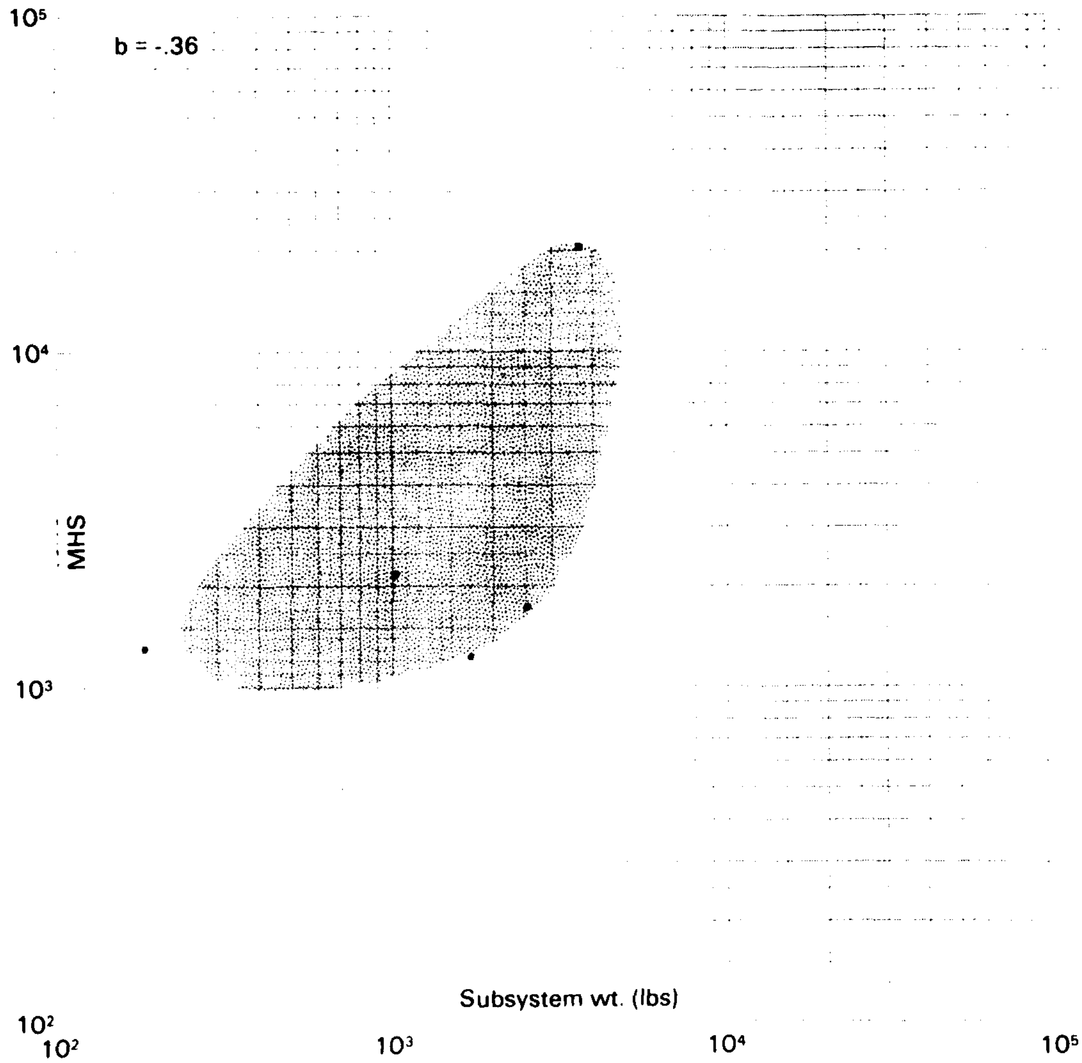


Fig. B-43—Production MHS* vs environmental controls weight

*100th unit cum ave value

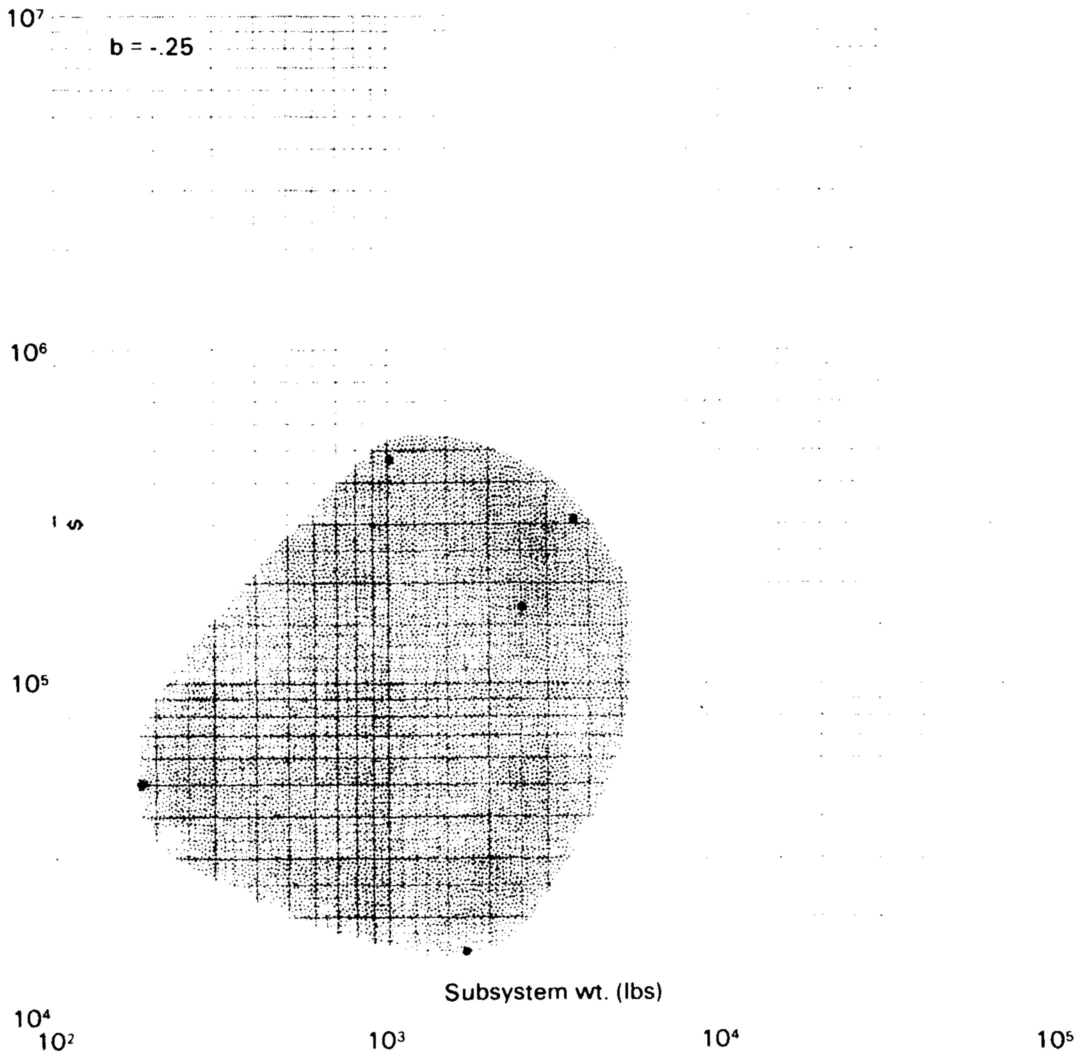


Fig. B-44—Material \$* vs environmental controls weight

*100th unit cum ave value

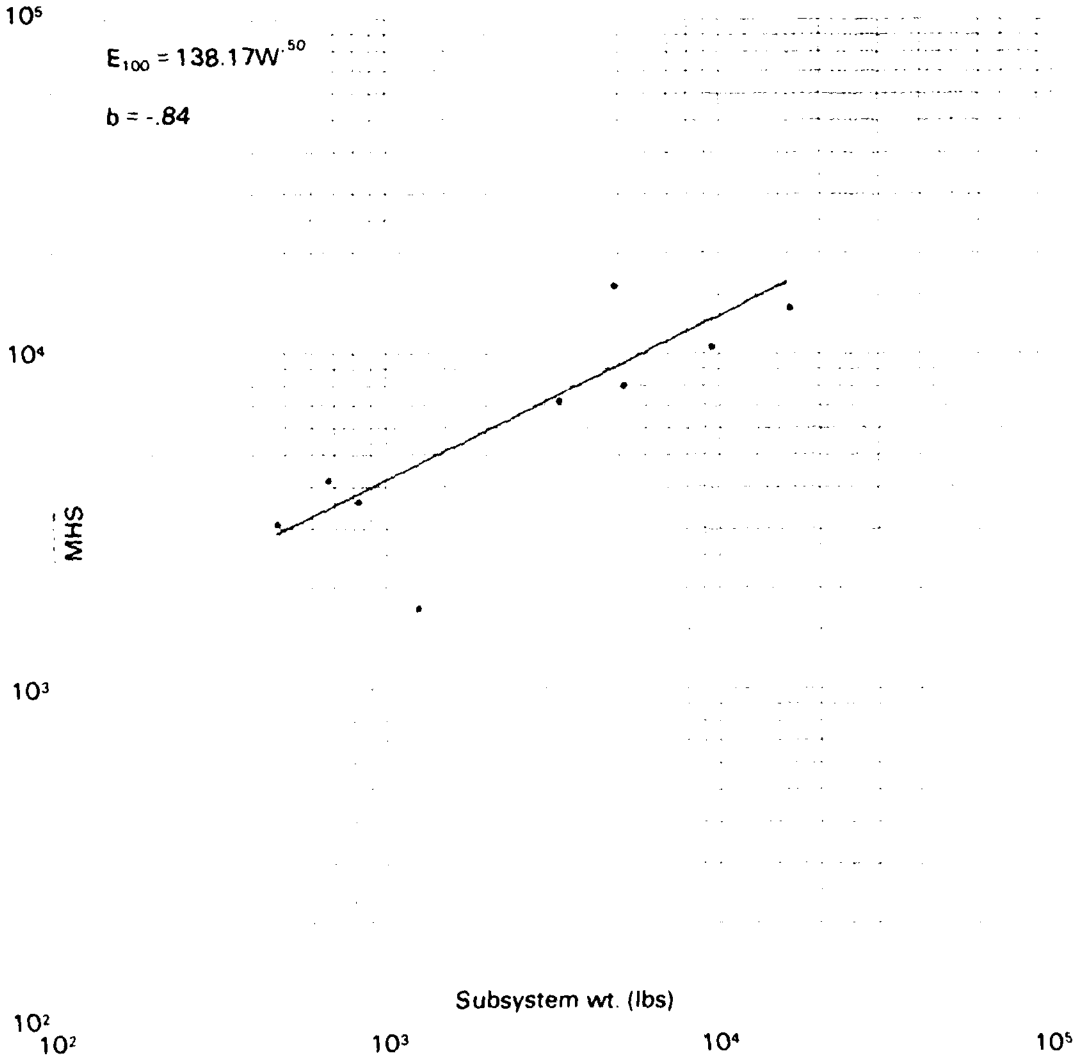


Fig. B-45—Engineering MHS* vs propulsion total weight

* 100th unit cum ave value

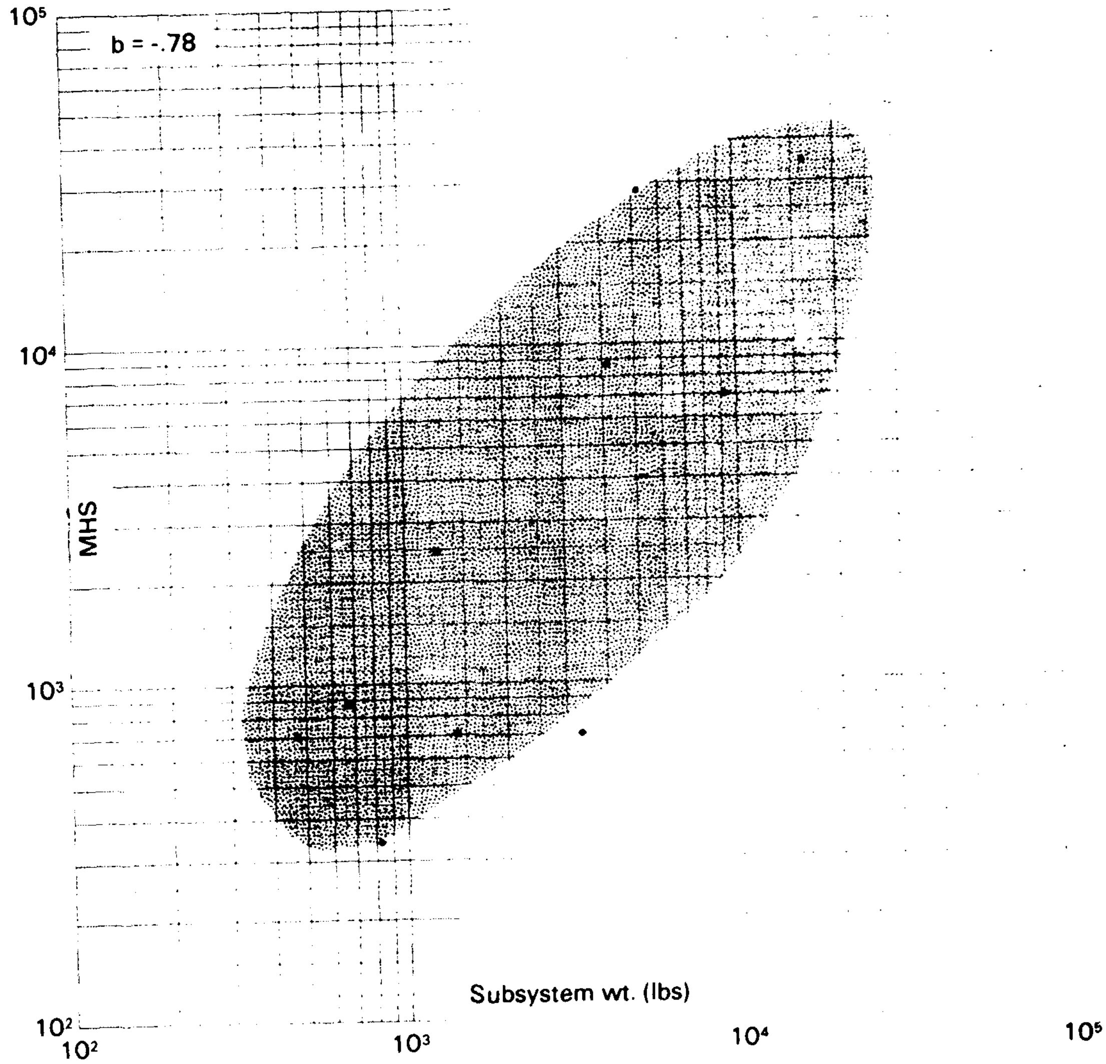


Fig. B-46—Tooling MHS* vs propulsion total weight

*100th unit cum ave value

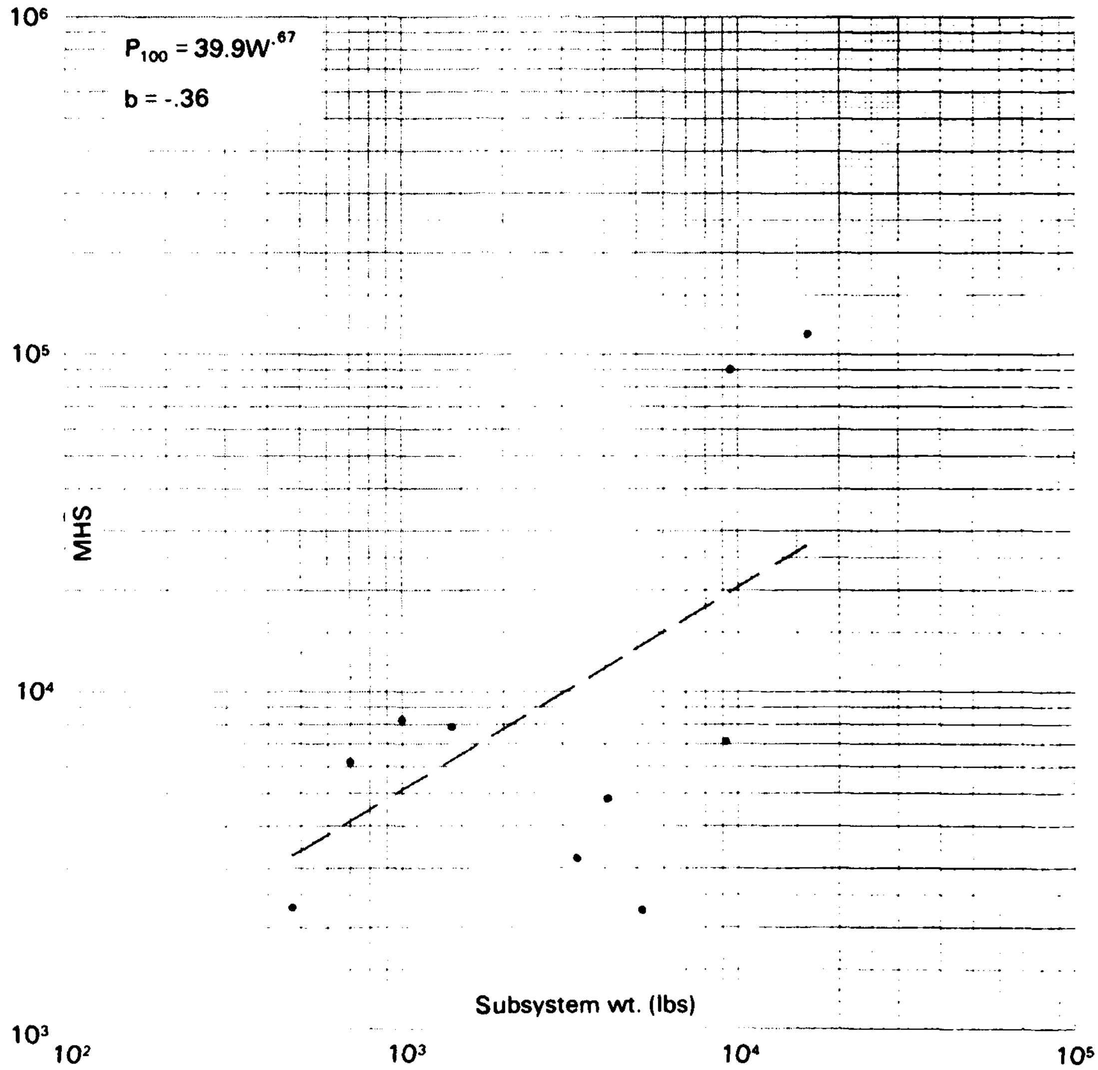


Fig. B-47—Production MHS* vs propulsion total weight

*100th unit cum ave value

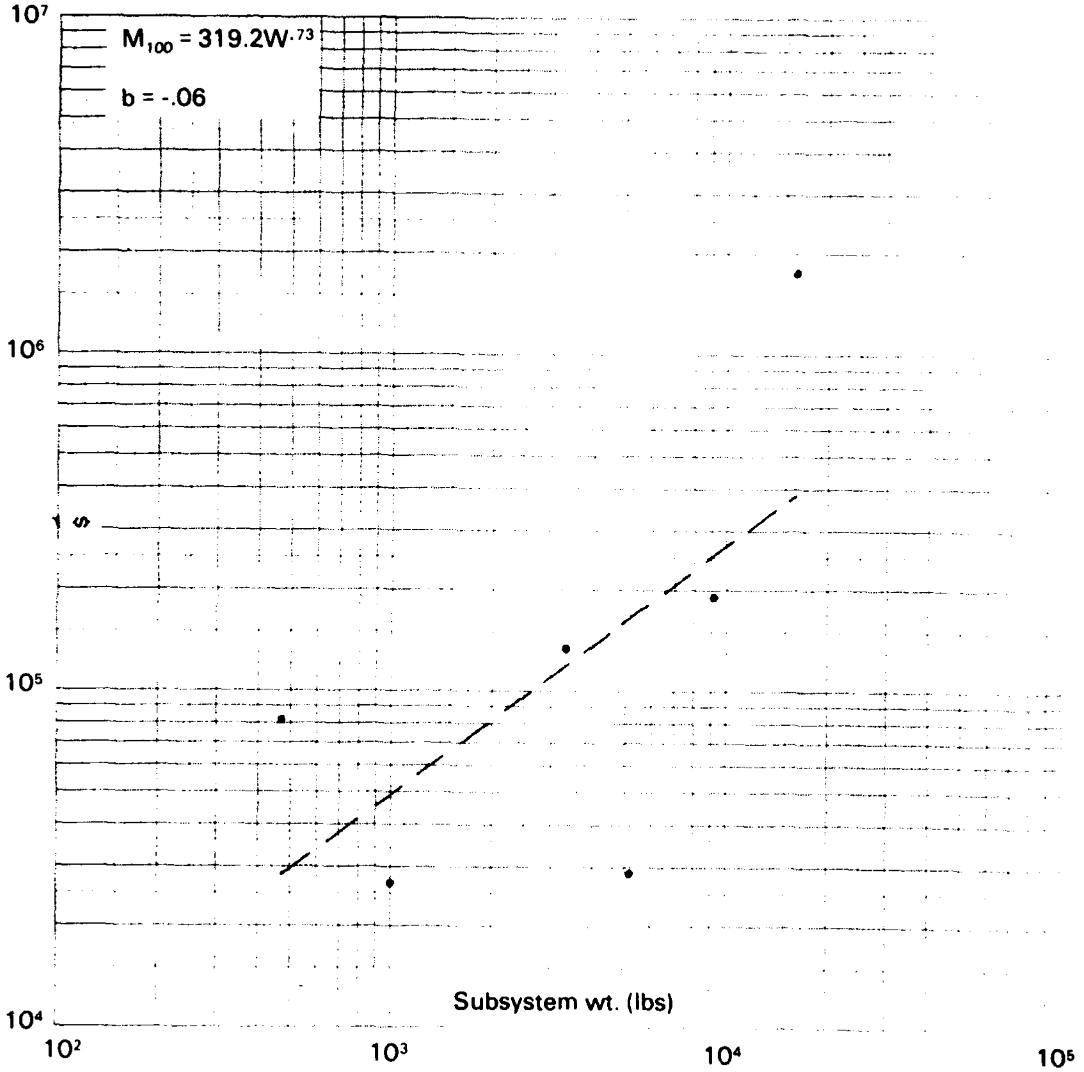


Fig. B-48—Material \$* vs propulsion total weight

*100th unit cum ave value

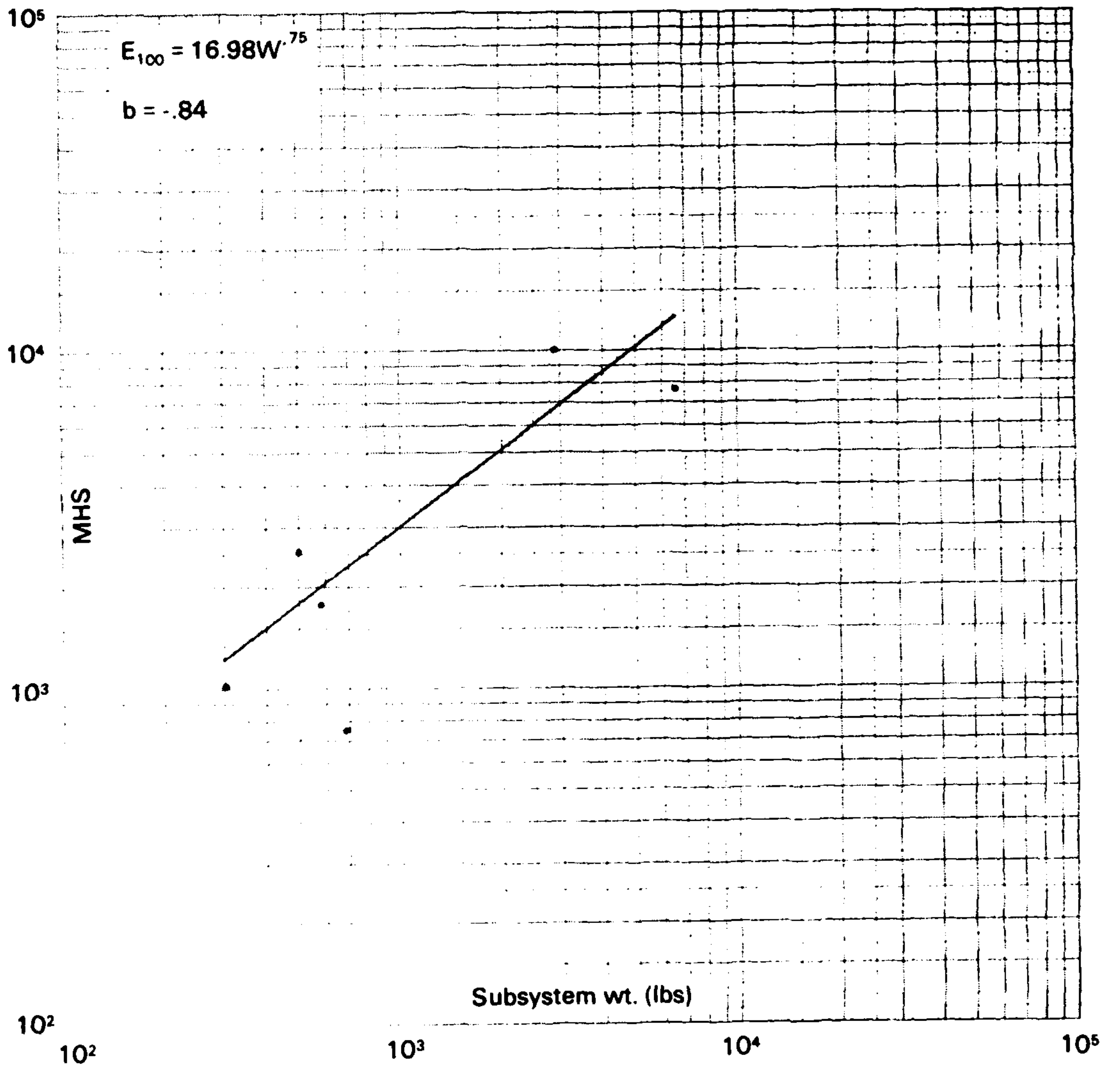


Fig. B-49—Engineering MHS* vs fuel system weight

*100th unit cum ave value

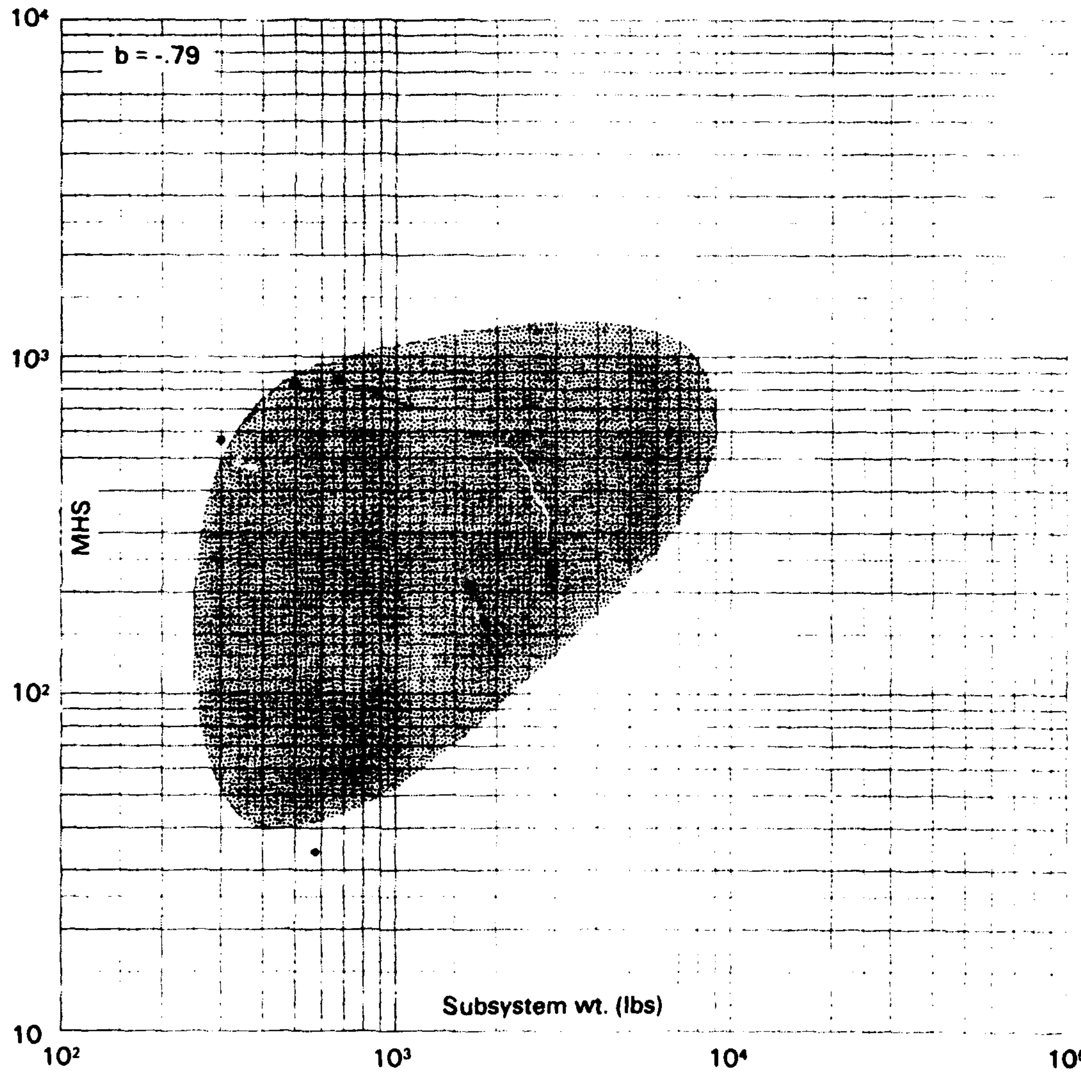


Fig. B-50—Tooling MHS* vs fuel system weight

*100th unit cum ave value

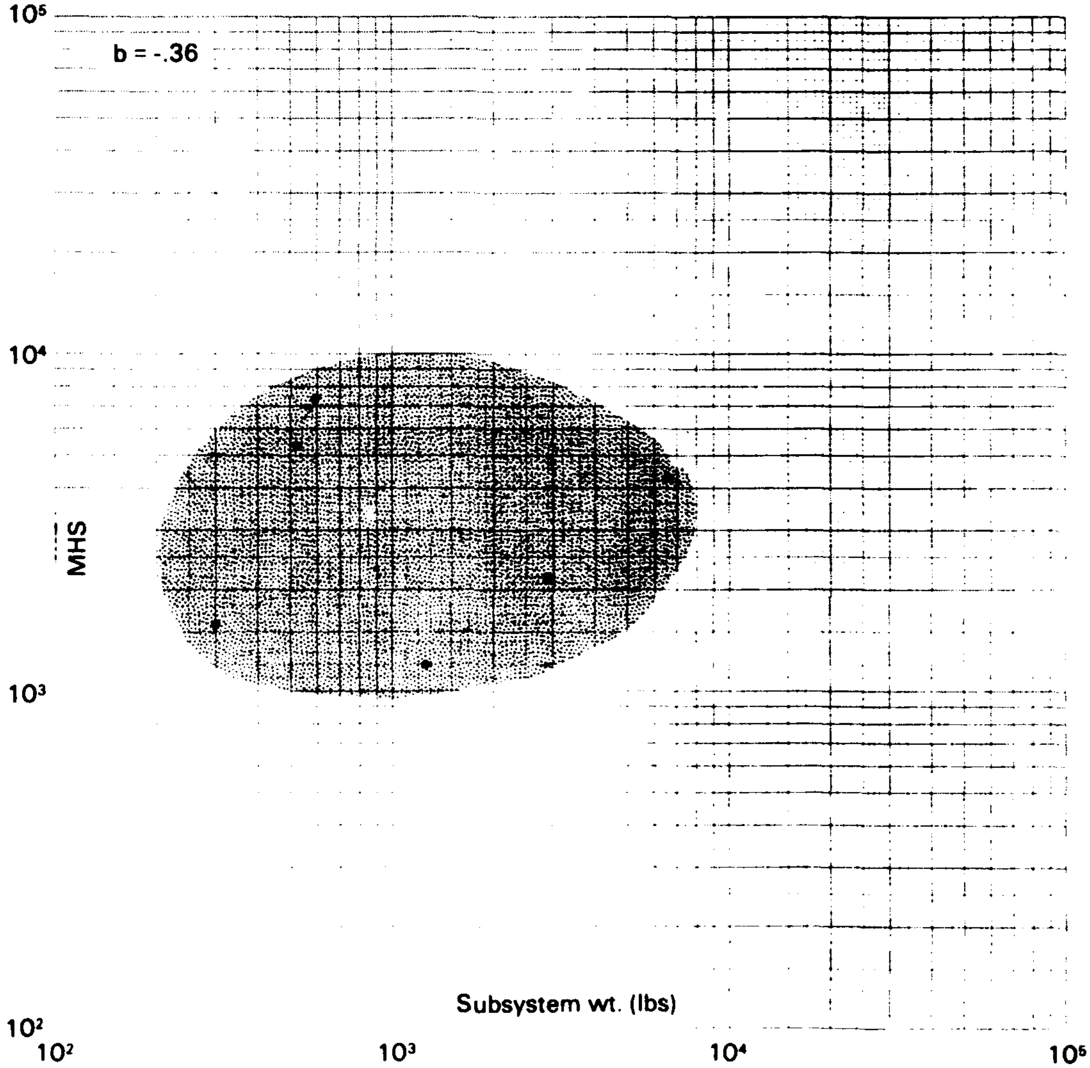


Fig. B-51—Production MHS* vs fuel system weight

*100th unit cum ave value

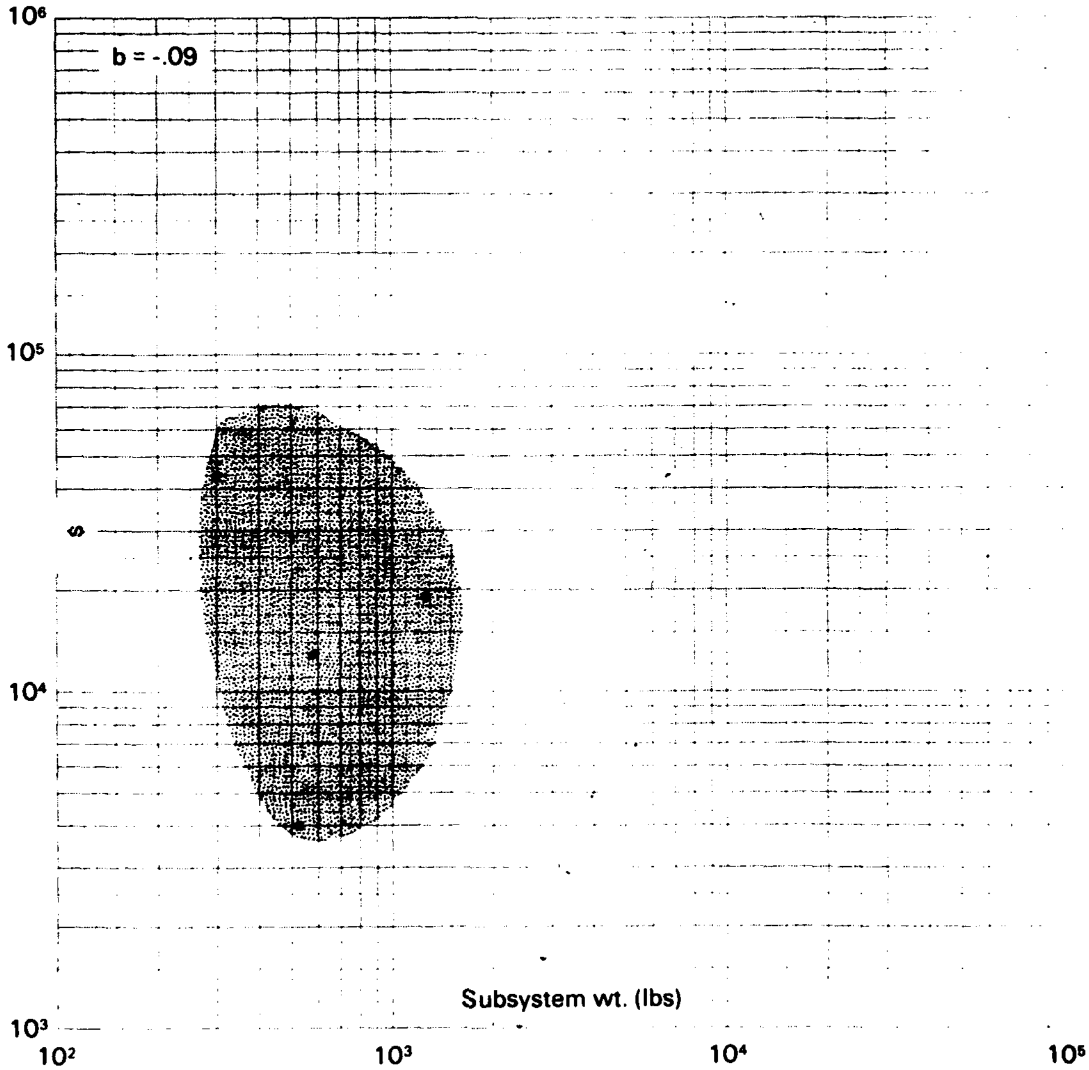


Fig. B-52—Material $* vs fuel system weight

*100th unit cum ave value

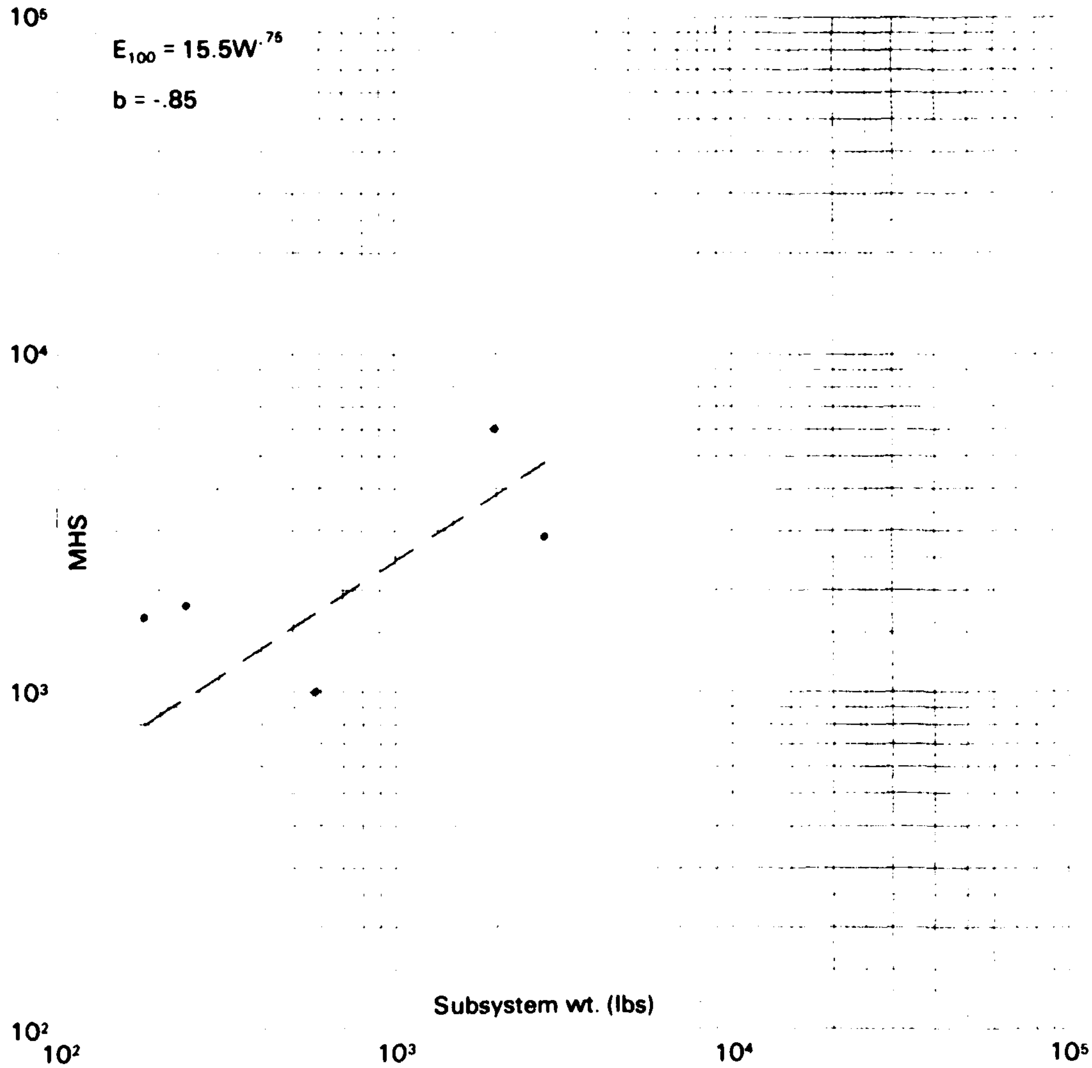


Fig. B-53—Engineering MHS* vs propulsion system weight

*100th unit cum ave value

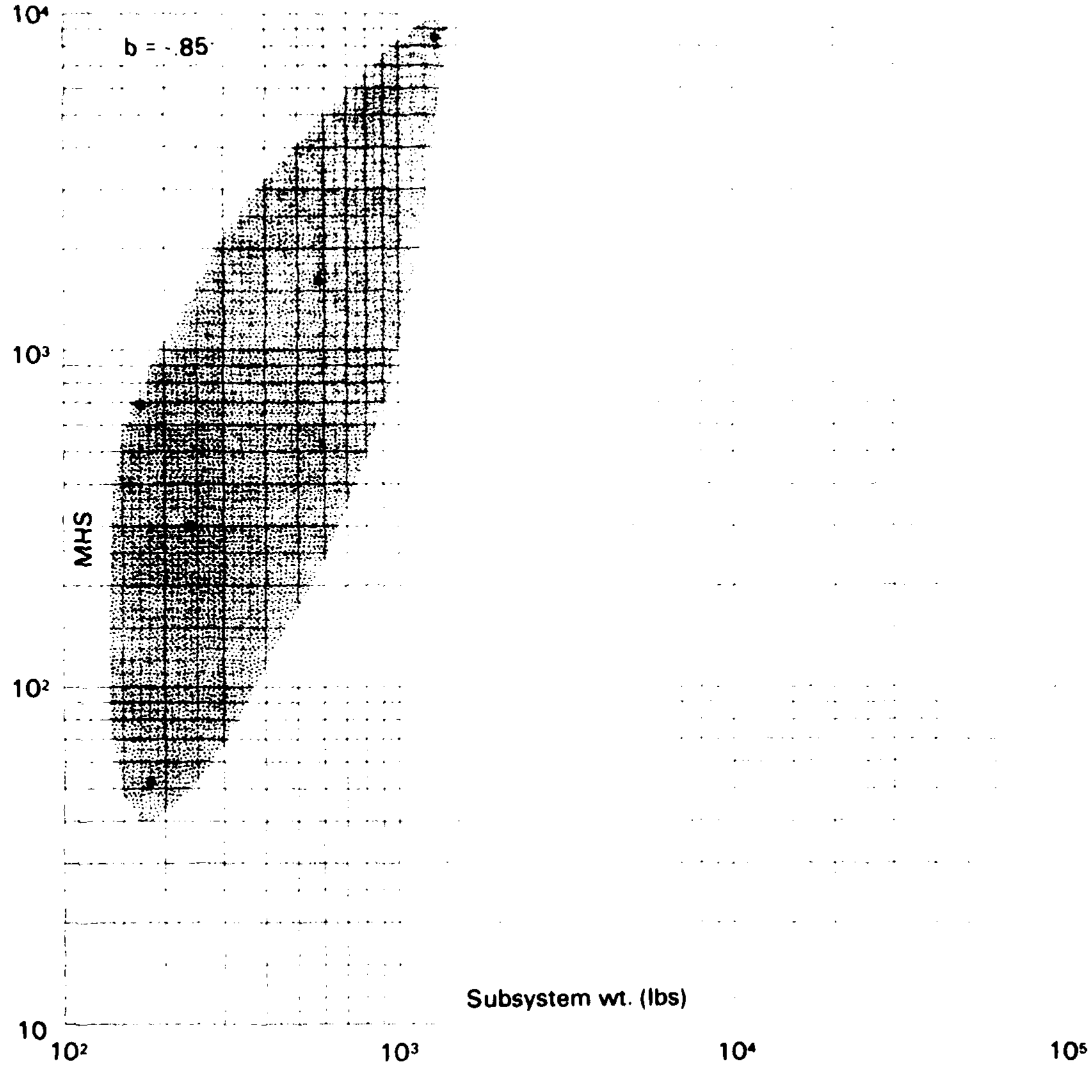


Fig. B-54—Tooling MHS* vs propulsion system weight

*100th unit cum ave value

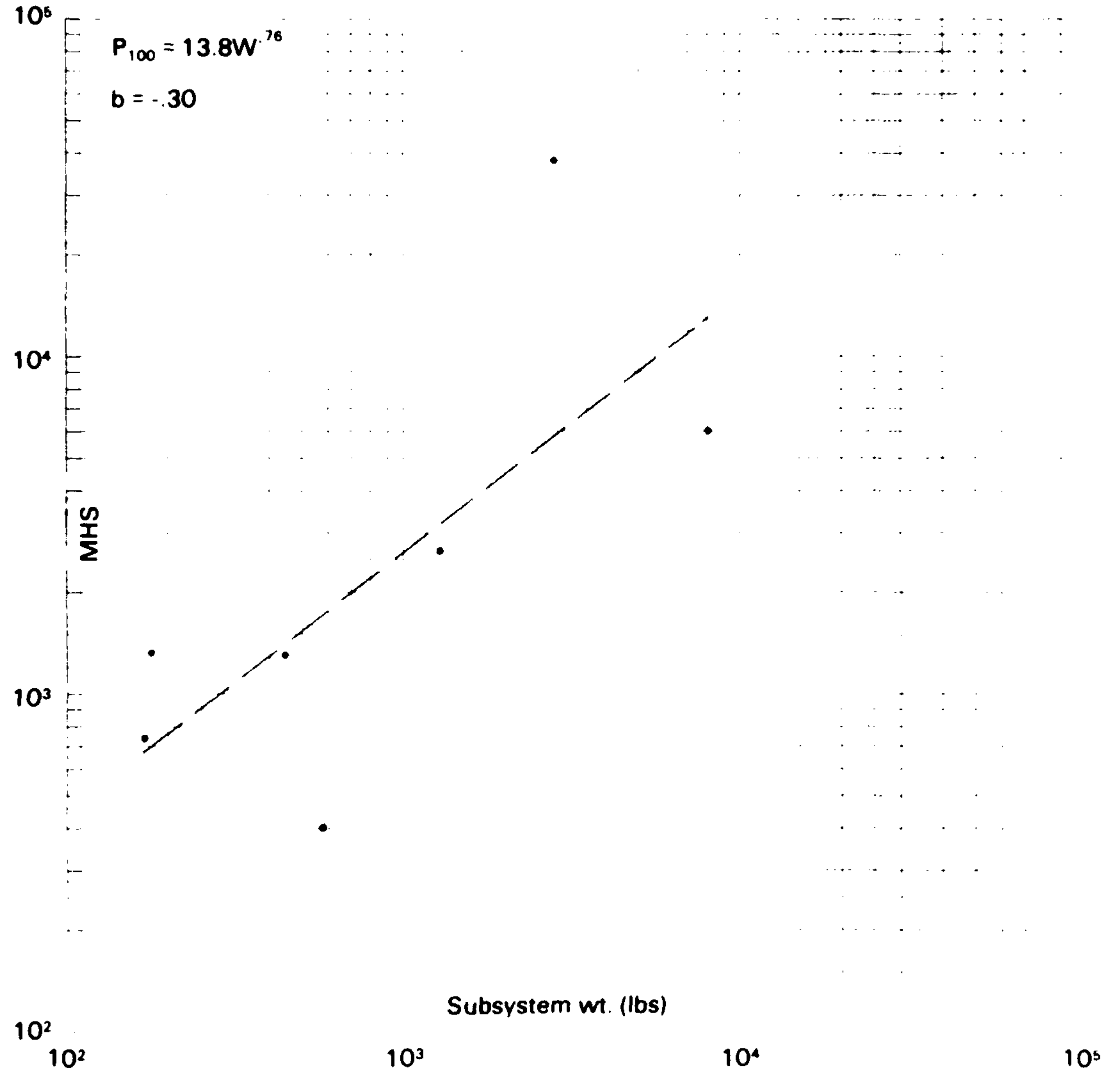


Fig. B-55—Production MHS* vs propulsion system weight

*100th unit cum ave value

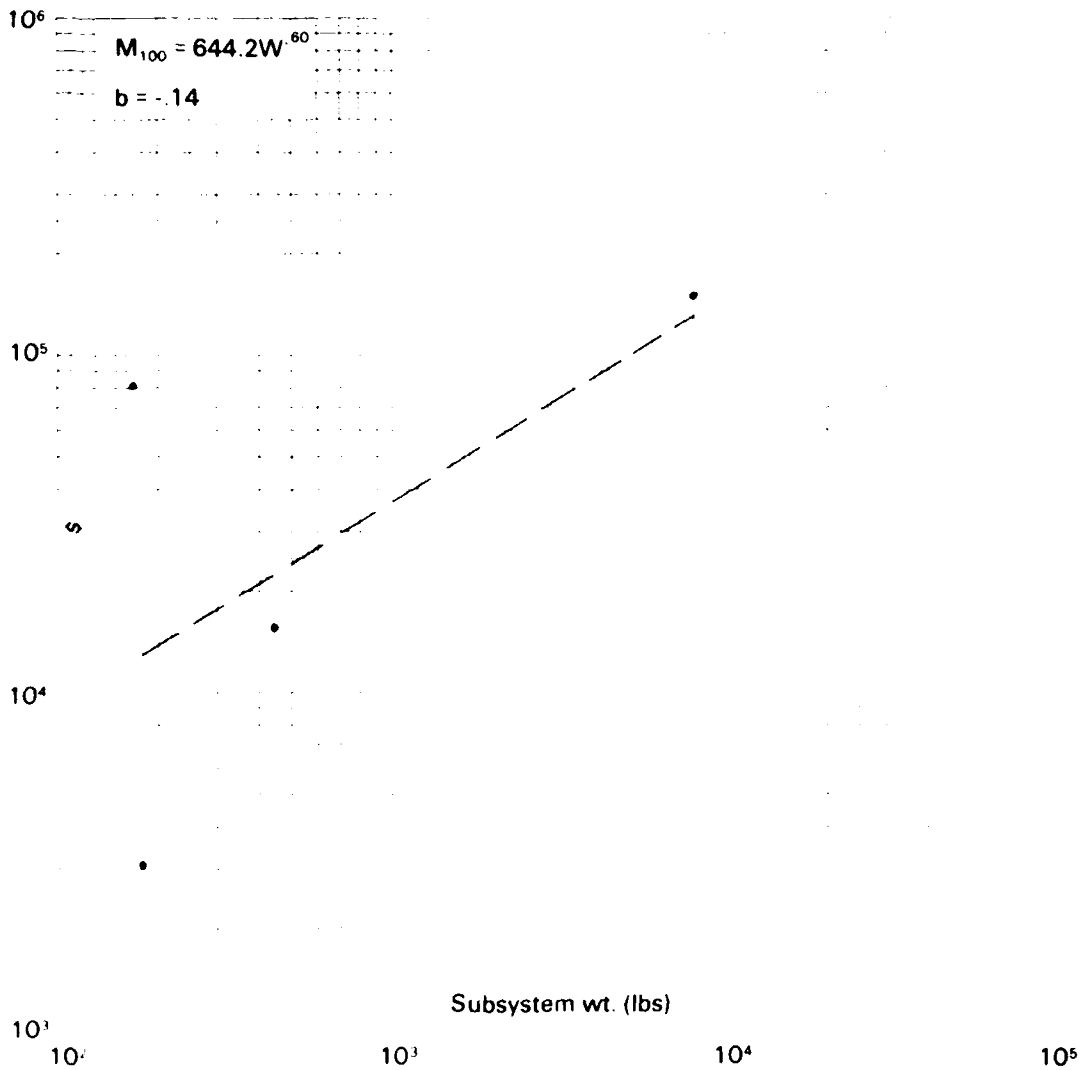


Fig. B-56—Material \$* vs propulsion system weight

*100th unit cum ave value

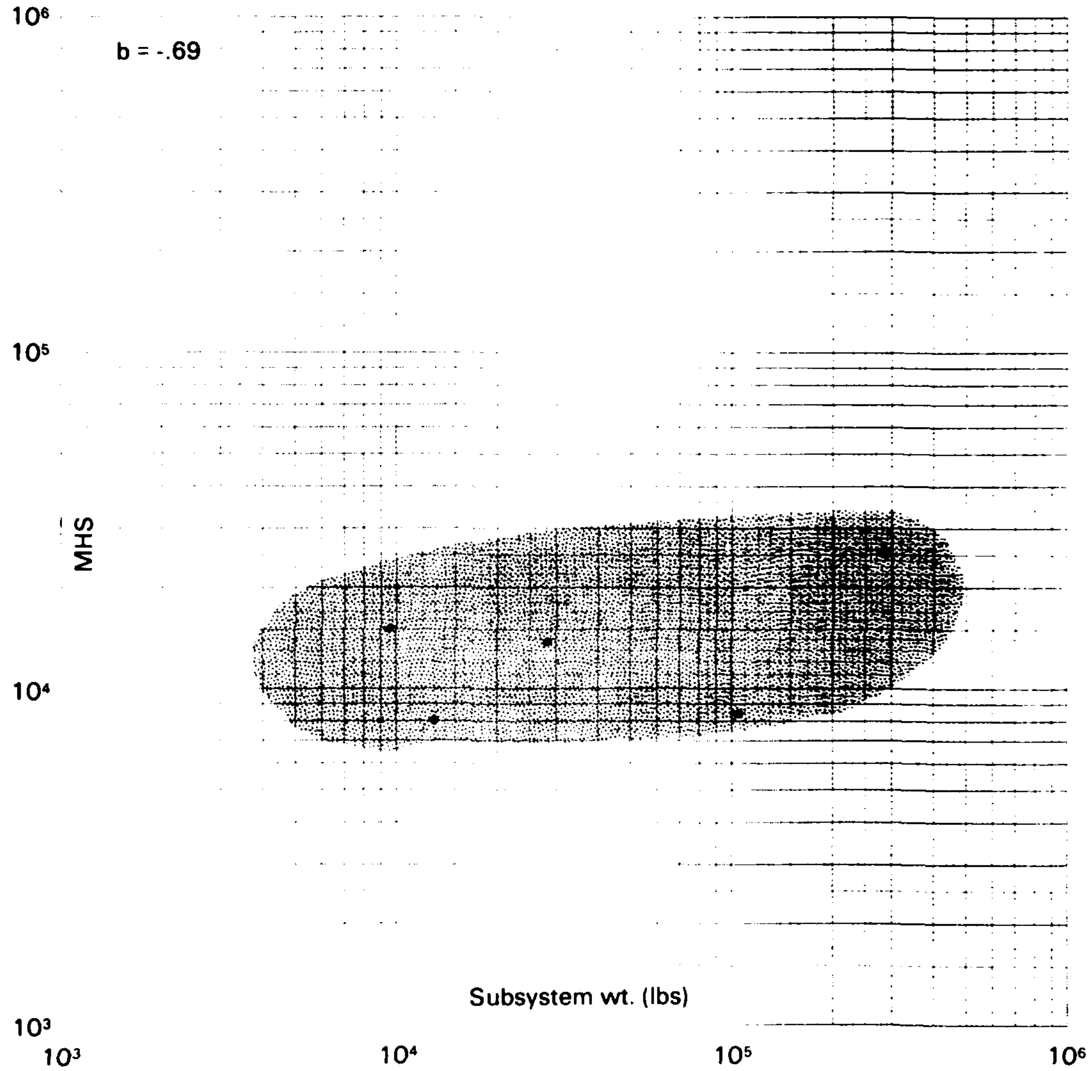


Fig. B-57—Engineering MHS* vs system integration weight

*100th unit cum ave value

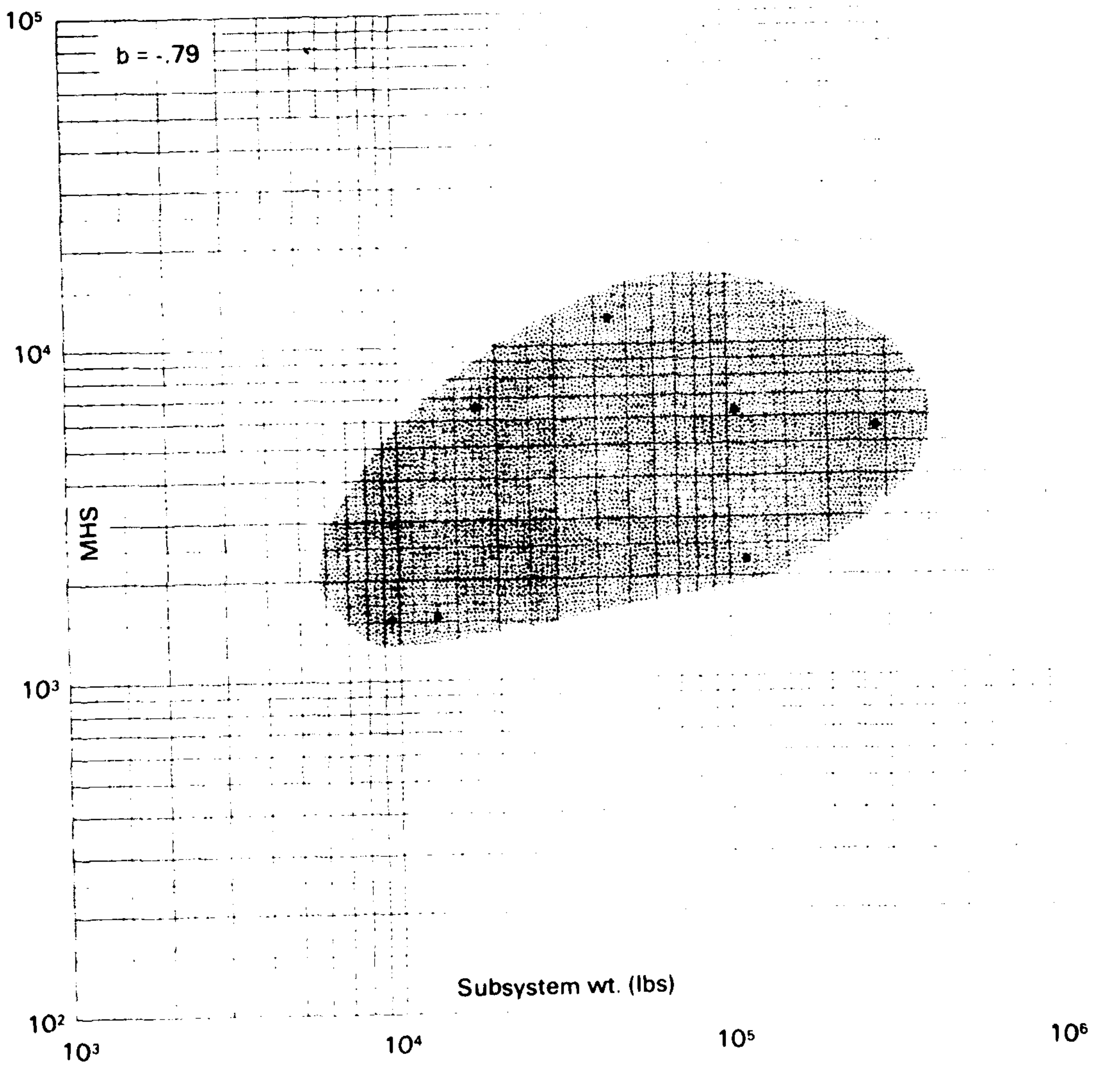


Fig. B-58—Tooling MHS* vs system integration weight

*100th unit cum ave value

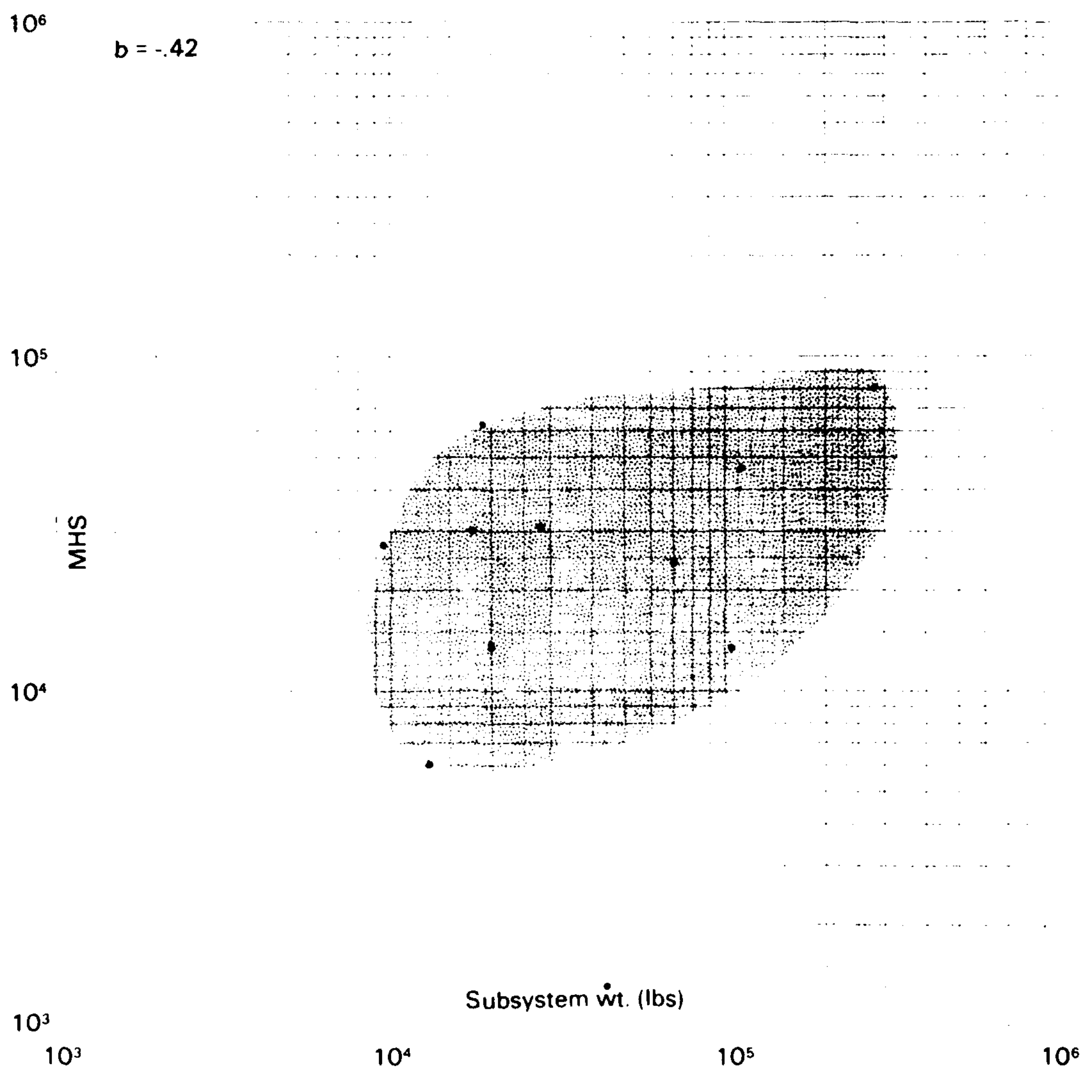


Fig. B-59—Production MHS* vs system integration weight

*100th unit cum ave value

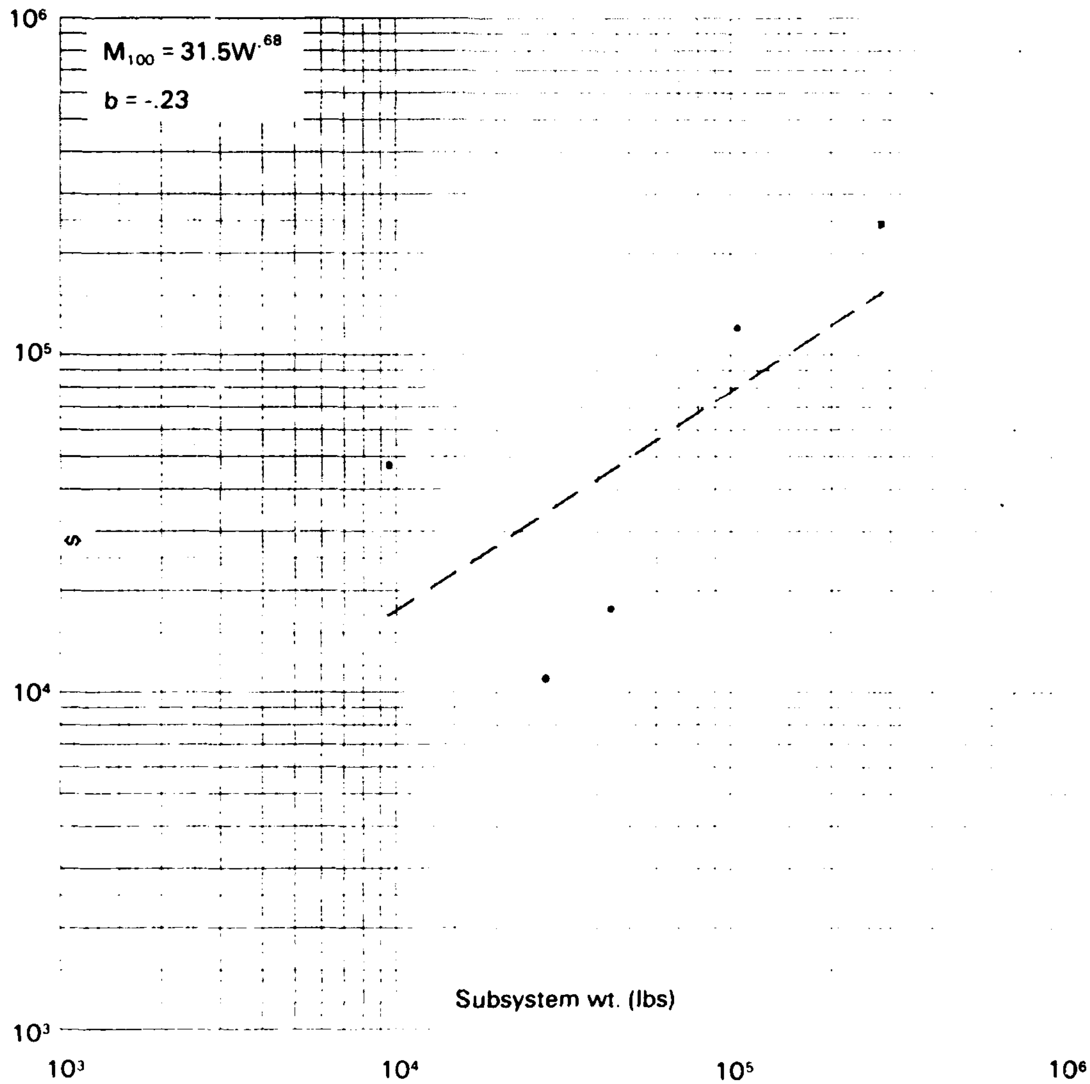


Fig. B-60—Material \$* vs system integration weight

*100th unit cum ave value

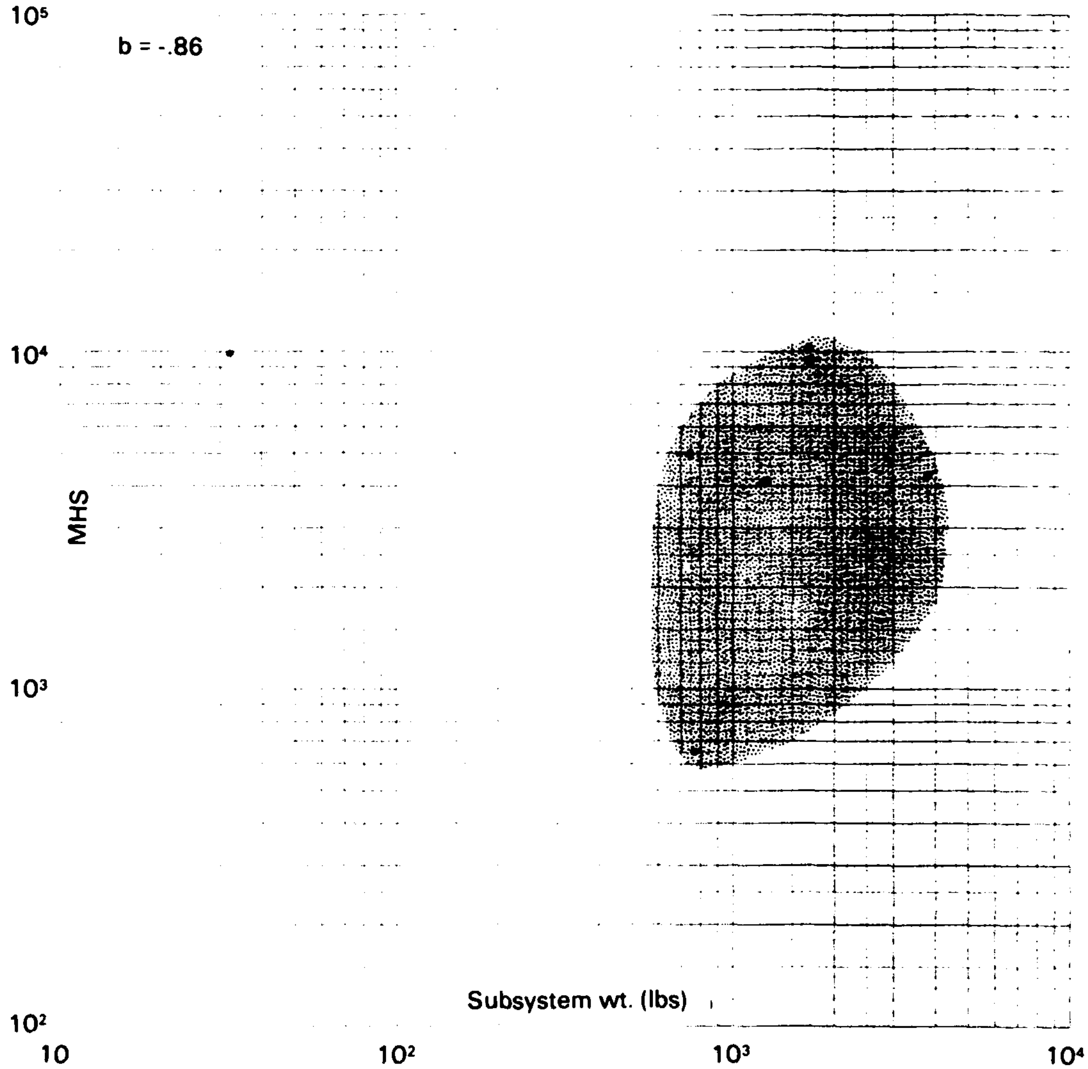


Fig. B-61—Engineering MHS* vs avionics weight

*100th unit cum ave value

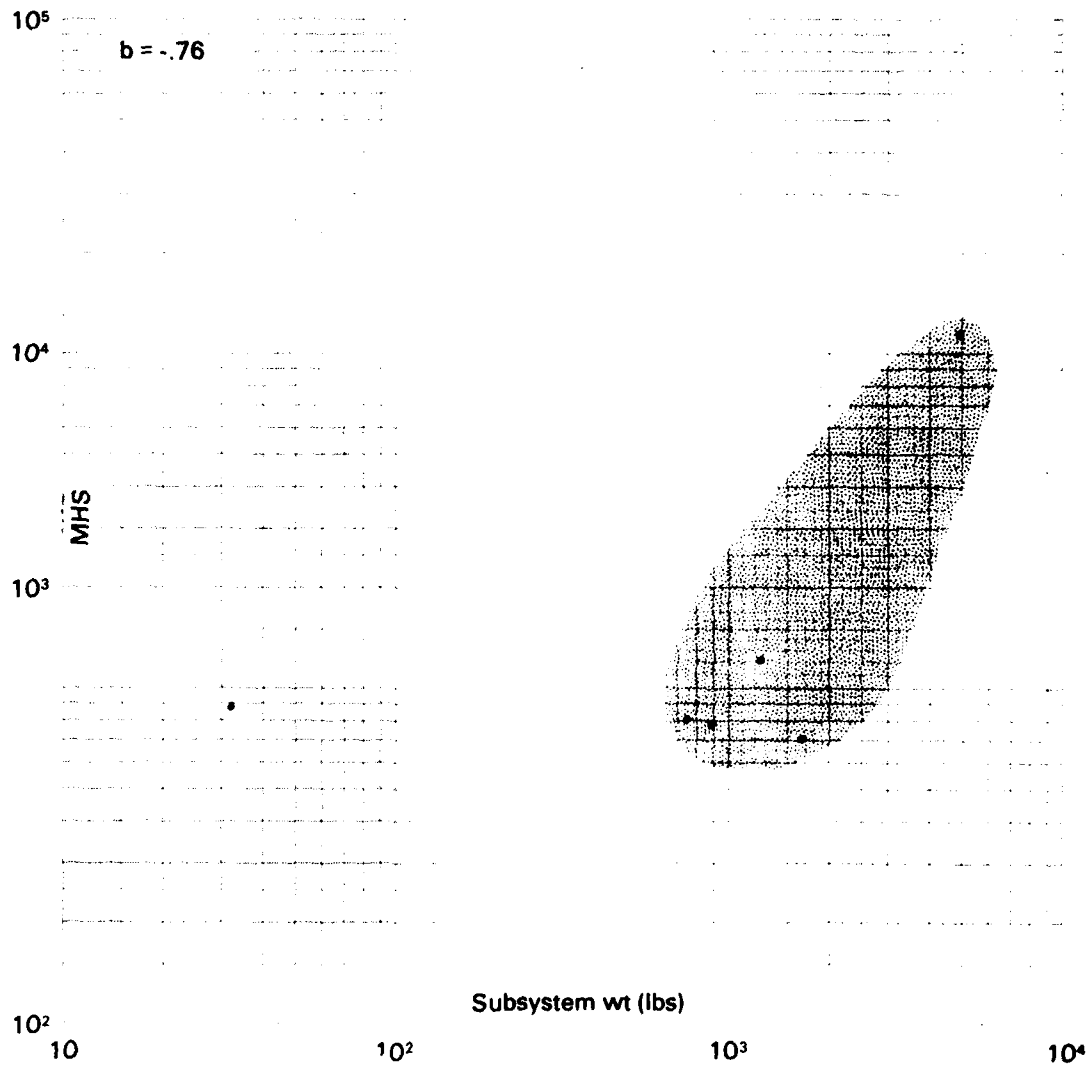


Fig. B-62—Tooling MHS* vs avionics weight

*100th unit cum ave value

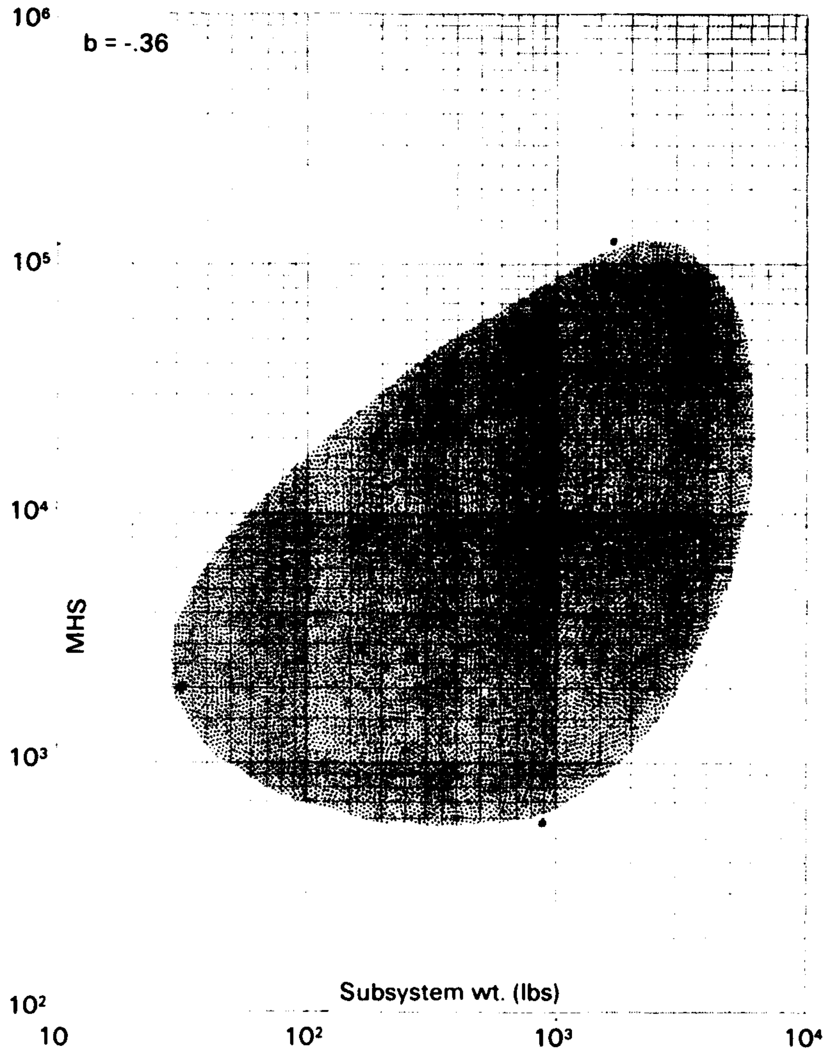


Fig. B-63—Production MHS* vs avionics weight

*100th unit cum ave value

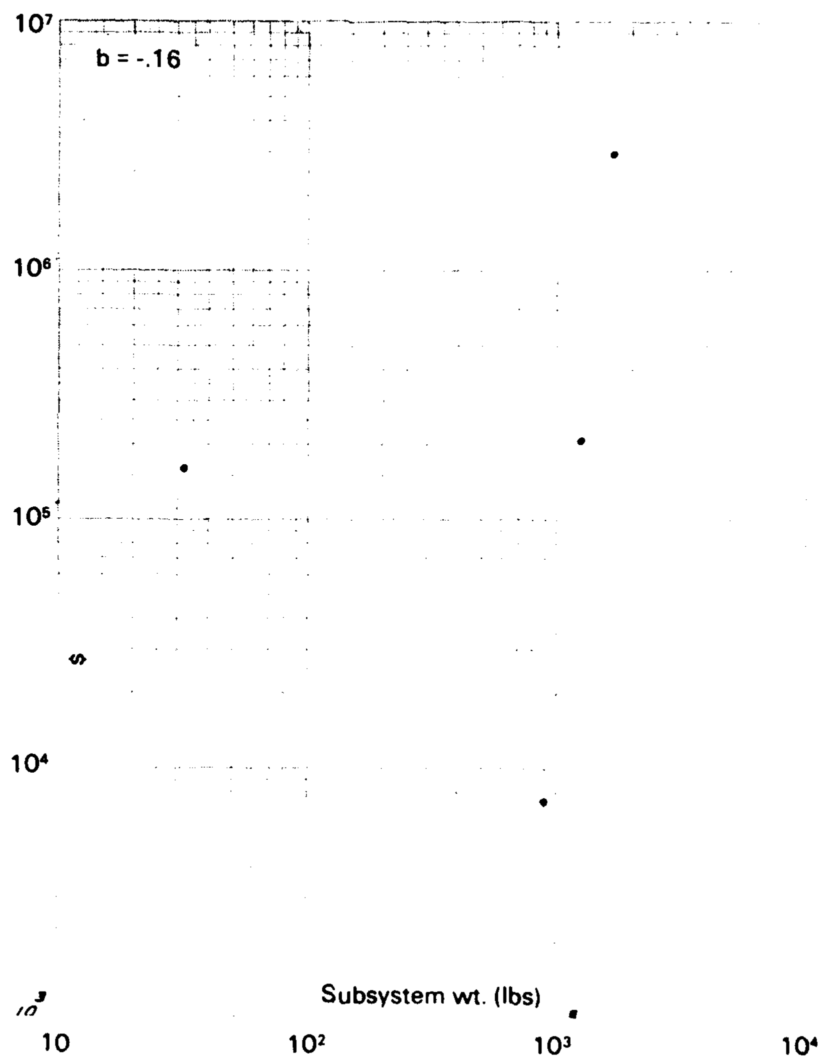


Fig. B-64—Material $* vs avionics weight

*100th unit cum ave value

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